Aalto University
School of Engineering

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Energy efficient shape optimization of multiple buildings

Thesis submitted for examination for the degree of Master of Science in Technology

Espoo 28.11.2016
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Diplomityön tiivistelmä

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Tiivistelmä

Energiatehokkuus ja rakennusten ympäristövaikutukset ovat suuressa osassa kansainvälisissä ilmastosopimuksissa asetettujen tavoitteiden saavuttamisessa ja päästöjen vähentämisessä. Energiatehokkuuden huomioiminen jo suunnittelun alkuvaiheessa parantaa rakennusten tehokkuutta huomattavasti. Rakennusten oikealla muodolla ja suuntauksella voidaan vähentää energiatarvetta jopa kolmanneksella.

Rakennusten optimointia pidetään yleensä aikaa vievänä prosessina, joka vaatii huomattavan määrän erikoisosaamista. Tässä diplomityössä luotiin yksinkertainen geneettistä algoritmia hyödyntävä simulointimalli suunnittelijoiden käytettäväksi konsepti vaiheessa. Rakennusten määrä pysyy vakiona simuloinnin ajan, mutta rakennusten määrän voi muuttaa helposti mallia muokkaamalla. Malli simuloi rakennusten energiankulutusta kansallisten rakennusmääräysten ja paikkakohtaisen säätiedon perusteella. Mallin rakennuksien julkisivuun on integroitu aurinkopaneeleita tuottamaan paikallista energiaa. Ratkaisuna malli antaa rakennuksille koon, muodon ja suuntauksen pienimmän löydetyn energiakustannuksen perusteella annetussa ajassa.

Mallia testattiin kahden paikan lähtöarvoilla: Helsingissä ja Bukarestissa. Kummassakin sijainnissa simuloitiin viisi eri tapausta vaihtelevilla rajoituksilla. Vaihtuvat rajoitteet koskivat ikkuna- ja seinäpinta-alan suhdetta, paikallisen tuotannon määrää ja rakennusten lukumäärää. Tulosten pohjalta malli reagoi vaihteleviin rajoituksiin odotuksien mukaisesti sekä samalla tavalla kuin muissa vastaavia ominaisuuksia käsittelevissä tutkimuksissa.

Tässä työssä käytetty malli huomioi vain rakennusten sähkönkulutuksen ja rakennuksen järjestelmät on asetettu toimimaan sähköllä. Joitakin osioita, kuten varjostusmallia, jouduttiin yksinkertaistamaan työhön käytettävien resurssien puitteissa. Mallin täyden potentiaalin arvioiminen vaatisi yksinkertaistettujen osioiden tarkentamista sekä useampien energiavirtojen tarkastelun lisäämisen malliin.

Avainsanat Rakennusten optimointi, geneettinen algoritmi, energiatehokkuus, paikallinen energian tuotanto, energian jakaminen

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Abstract of master's thesis

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Abstract

Energy efficiency and environmental impacts of buildings take a major part in decreasing emissions to achieve goals set in international climate agreements. Taking energy efficiency into account as early as in conceptual phase has a significant effect on the performance of a building. By choosing the optimal building shape and orientation, the energy consumption of the building can be reduced by one third.

Building optimization is considered as a time-consuming process that requires a significant level of expertise. In this thesis, a simple optimization model using genetic algorithm was created for designers to review concepts with multiple buildings during the conceptual design phase. Number of buildings is fixed during the simulation, yet the model is easily modified to match the desired number of buildings on a chosen site. The model simulates energy consumption considering national building regulations and the respective location based weather data. Simulated buildings are integrated with façade photovoltaics as onsite production. As a solution, the model gives the sizes, shapes and orientations of the buildings for the setting with the smallest energy costs found in the time given for the simulation.

The model developed in this thesis was tested in two different locations, Helsinki in Finland and Bucharest in Romania. Each location was tested with five different cases with varying constraints on window-to-wall ratio, amount of onsite production and number of buildings. Based on the results the model reacts to studied properties as expected and similarly than as other studies considering similar actions.

Model used in this thesis accounts only for buildings consuming electricity and building systems were set to use electricity. Some features of the model were simplified, e.g. shadowing model, in respect to the resources allocated to the thesis. To review the full potential of the model, additional development on simplified features and alternative energy forms should be conducted.

Keywords Building optimization, genetic algorithm, energy efficiency, onsite energy production, energy sharing

Foreword

I would like to thank my professor Risto Lahdelma for introducing me to the evolutionary algorithms and suggesting this subject for my thesis. Special thanks go to my instructor Nusrat Jung, who has encouraged me during the work and pointed me in the right direction on the way. Her enthusiasm towards the subject motivated me to perform better than I could have imagined.

Finally, I would like to my family and friends for supporting me during these years of studying. Thank you, Oona, for listening and supporting me. Without you this thesis would not be ready. Additional thanks go to our dog, Jekku, who reminded me that other things also exist during long days of studying.

Helsinki 28.11.2016

Mikko Virta

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Nomenclature

Variables

A	[m²]	area
F		view factor
G	[W/ m²]	solar irradiation
H		shading factor
T	[°C]	temperature
P	[W]	power
Q	[W]	heat energy
R	[J/K m]	heat conductivity, U-value??
V	[m³]	volume
c	[J/kg K]	heat capacity
g		g-value of the window
s	[°]	slope of the surface
γ	[°]	azimuth angle of the surface
γ_s	[°]	azimuth angle of the sun
δ	[°]	declination angle
ε		efficiency of heat recovery
η		efficiency
θ_i	[°]	angle of incidence
θ_z	[°]	zenith angle
ρ	[kg/m³]	density
$\emptyset$	[°]	latitude
ω	[°]	hour angle

Acronyms

BIPV	building integrated photovoltaics
GA	genetic algorithm
HVAC	heating, ventilation and air conditioning
NZEB	net-zero energy building
nZEB	nearly zero energy building
OEF	onsite energy fraction
OEM	onsite energy matching
PV	photovoltaics
ZEB	zero energy building

1 Introduction

Energy efficiency and environmental impacts of buildings play a major role in decreasing emission and achieving the goals set in international climate agreements. In the U.S., building sector accounts for more than 40 % of the primary energy consumption and 70 % of electricity consumption (U.S Department of energy 2011). The energy efficiency of buildings has become more and more important part of the designing process of buildings but also considering the whole resource depletion and waste emissions during the whole life cycle. Improving the energy performance of both existing and future building stock has become essential to achieve EU climate and energy objectives, specifically a 20% reduction of greenhouse gas emissions, 20% of energy generated from renewable sources, and 20% increase in energy efficiency of buildings by the year 2020 (European Parliament 2010). Taking energy efficiency into account in the conceptual stage can make a significant difference in building energy performance and by simply making buildings with optimum shape and correct orientation can reduce the energy consumption by 30–40 % (Wang et al. 2005).

By using building optimization, it is possible to find the optimal values for the building design, energy consumption, on-site energy system etc. Regardless of the objective, the optimization model will have numerous decision variables and a huge number of possible solutions (Palonen et al. 2013). Building optimization problems are mostly so complex that they cannot be solved with conventional gradient-based methods based on mathematical procedures that are highly dependent on the initial guess. Gradient-free methods offer in turn a possibility to solve the building optimization problems. They are based on stochastic approaches and one widely accepted is the Genetic Algorithm (GA) (Holland 1992) developed by in the 1970s (Magnier & Haghighat 2010).

Dynamic energy simulations have been one of the key features when planning a nearly net-zero energy buildings (NZEB) (Jung et al. 2013). Multiple studies have been conducted for small residential buildings, at the same time very few detailed studies exist for large scale multi-story buildings. The main reason behind this is that required input data from designers to engineers for simulations is not available at early planning stages. It has been debated that smaller scale simulation studies can provide more accurate assessment, as when there are few parameters, it becomes easier to assess the results. Respectively, dealing with large scale building models is more time consuming and difficult, and assessing impacts of multiple buildings on the site are even more challenging. Despite the challenges, it consequently important to study and assess multiple buildings to understand their energy consumption and production potential.

The architectural design of new buildings becomes a significant component for realizing energy efficiency targets, especially considering the key decisions that are made during the design process. For example, a standard indicator of building energy performance is annual specific energy consumption (kWh/m^2) as a function of climate, envelope design, heating ventilation and air conditioning (HVAC) systems, and occupant behavior, among other parameters (IEA 2013). Very seldom the key decisions which affect the building performance are assessed in detail during the design process. The main reason behind this is that the design process during the planning stage is very difficult to translate to a detailed building model as required by the conventional energy simulation tools. Also, the dynamic energy simulation models require a significant amount of input variables which are not clear during the initial design and planning phases. Even if the building performance assessment is made, it's not considered accurate, and thus very few conclusions made from it are implemented in the actual design.

Use of different simulation tools should be relevant to the purpose of the outcome. The demand in the accuracy of building details in conceptual phase designing is totally different from final structural plans and the simulation method should be chosen as sufficient with respect to the requirement. To represent the different simulations tools, level of detail and to define the role of modeling, a three-dimensional conceptual problem space was created by (Athienitis et al. 2015) and is represented in Figure 1.

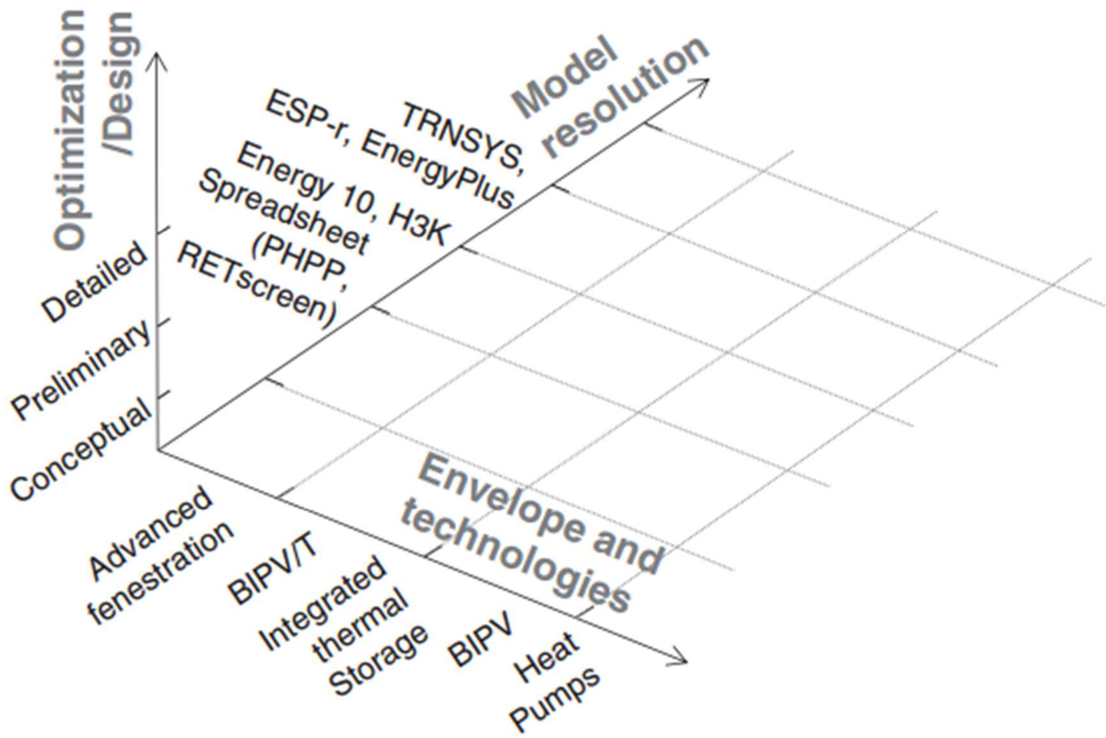


Figure 1 The 3D matrix representing model resolution, technologies and design state (Athienitis et al. 2015)**.**

The goal of this study is to develop and demonstrate a simplified model which can automatically optimize and generate the shape of the building based on selected energy efficient parameters to inform building designers. This model can be used as early as in the conceptual design phase of a building while considering the energy generation and consumption patterns based on the 'obtained optimized' shape of the building. This model uses building specifications based on building regulations and local weather data as input data to decrease the number of variables efficiently, yet it is detailed enough to achieve results corresponding to the simulation environment and actual conditions based on location. Robustness of the model makes to model fast enough for designers to use in the early design phases as it is the most suitable time to influence on the shape and orientation of the building (Häkkinen et al. 2015). Case studies in this thesis were conducted to confirm that the simplified simulation features have equal effect as output when compared to smaller scale simulation studies and can provide substantive results to inform key decision makers during the design process.

Model is spreadsheet based and operates with genetic algorithm built in Microsoft Excel. This enables the user to set the starting values as desired or randomly and still find an optimal solution. With manipulation of the initial starting values and the GA engine settings, the user can steer the model to look for global optimum or to fine-tune the initial setting. These attributes make the model versatile and easy to use in as early as conceptual phase and enable to test and developed multiple concepts efficiently. In reference of the conceptual problem space presented by Athienitis et al. (2015), this model sets as conceptual optimization at spreadsheet resolution with a few integrated technologies.

With resources allocated to this thesis, some limitations were made to simulation features. Minor parts of the building envelope, such as cold bridges, were not accommodated, and the energy consumption model did not include heat capacity of structures. Also, building regulations in destination countries were not identical and every aspect could not be considered correspondingly. The model doesn't involve any other costs than the costs for purchased energy and compensation for sold excess energy. The costs introduced should not be compared between different location and the cost embodies only the benefits of self-produced energy as the ratio of compensation of export energy to the price of import electricity. Review of performance of the model was conducted as comparison of results based on different input values and constraints.

This thesis consists of six sections: introduction, theory section, methodology section, results section, discussion section and conclusions. In the theory section, background literature is presented with the theory applied on the developed model. Methodology section explains the different criteria selected in the optimization model and introduces the optimization process. All optimization and fixed variables and variable level constraints are introduced in the methodology section. Results section consists of the results and interpretation of the case results in two ways: Case comparison and location comparison. The case comparison compares the results case by case and reviews the effect of different location in respect of the designed cases. Location comparison compares the different cases in the same location and reviews the how different building specifications effect the model when the surrounding environment stays the same. The total performance of the developed model is reviewed and compared in the discussion section and identification of further research is presented in conclusions.

2 Theory

This section presents the previous studies as reference to the methodology adopted for developing this model and the theoretical background of the multiple building energy optimization model.

2.1 Background literature

Term optimization often refers to a procedure of making something work as efficiently as possible or mathematically finding the optimum of the objective function. In building optimization the procedures are parts of building systems or structures, e.g. thickness of insulation, windows sizes, building ventilation system etc. (Nguyen et al. 2014).

In the beginning, approach known as “parametric simulation method” was commonly used to improve building performance. Parametric simulation method means changing one parameter at a time while keeping other parameters the same and trying to enhance the performance. This method is very time-consuming because interactions between parameters are sometimes non-linear (Nguyen et al. 2014).

Finding the optimal solution in less time and effort by use of computers and iterative methods where the optimal solution is found via numerous of approximations had a great impact on the development of the building simulation. These methods are often referred as ‘simulation-based optimization’ or ‘numerical optimization’. Earliest stages of simulation-based building optimization can be traced in the 1980s when computational science and mathematical optimization methods had major development steps. One of the pioneer studies in the field of building optimization is direct search method for HVAC optimizing by James A. Wright in 1986. The major increase of the number of optimization studies in building science did not start until the 2000s (Nguyen et al. 2014).

Since then many different optimizing tools have been developed to assist designers in finding energy efficient building designs. Different tools focus on different factors, such as end-use operating energy consumption, heating and cooling energy, building envelope etc. In studies which handled only one objective criterion, e.g. operating energy consumption, the proposed solution turned out to have excessive amounts of insulation and thus was not cost-effective. Some studies have introduced life cycle costs to overcome this issue (Wang et al. 2005).

Multi-objective optimization models have made more complex building simulations possible as it becomes possible to consider more than one fitness criterion in the optimization (Wang et al. 2005). With multiple objectives, the solution space can become so complex that the term optimization in building performance simulation does not anymore mean finding globally optimum solution but an iterative improvement process to find sub-optimal solutions (Nguyen et al. 2014).

Recently simulation-based building optimization have become efficient tools to measure needs for low-energy houses, passive houses and net zero-energy buildings (NZEB) (Nguyen et al. 2014). Environmental agreements and directives have motivated the building optimization by assessing objectives to reduce building related emission and energy use, e.g. 20 % reduction in greenhouse gas emission and primary energy consumption of buildings in European Union (European Parliament 2010) and for example, (Hamdy et al. 2013) introduced a method to calculate cost-efficient and nearly net zero-energy building (nZEB) performance level single detached house in Finland. Results of this and other relevant studies (Jarek Kurnitski et al. 2012), (Buildings Performance Institue Europe (BPIE) 2012) and (D'Agostino 2015) suggest the implementation of onsite renewable energy production to nZEB is the most economical solution. These studies set mainly the optimization boundary on one building level and in the solution energy production is maximized in terms of the one inspected building. When the system boundary is extended to correspond to multiple houses combination of the separately simulated solution may not be efficient.

Ala-Juusela et al. (2015) conducted a study on how to measure neighborhoods energy use when aiming for energy positive neighborhood. Energy positive neighborhood is defined as an area whose annual energy production exceeds the annual energy demand. These areas develop energy system from current centralized system towards more complex system where the role of producer and consumer becomes unclear. This shift needs to be taken into account when designing the infrastructure in urban areas. Besides, Study by Kilkiş (2014) concludes that low level of integration of energy system in net zero exergy system may lead to inefficiencies in term of waste of energy.

2.2 Theoretical contents

This section presents the theoretical content which provided the framework to develop the optimization model. The contents are divided into three main themes: Genetic algorithm, building optimization boundaries and the theoretical content of building optimization model.

2.2.1 Genetic Algorithm

As mentioned before, efficient building optimization requires gradient free algorithms to find the solution. One of the most applied algorithms is an evolutionary algorithm created by JH Holland in the 1970s called genetic algorithm (Magnier & Haghighat 2010).

GA mimics the natural biological evolution and operates on a population of potential solutions. GA evaluates the population based on the fitness function and uses the best solutions to create a new population to find even better solution.

The GA process starts with the initial population generated with random number generator based on given initial values. The algorithm organizes the vector of decision variables for each solution as equally long strings of data, called chromosomes. Solutions, which gives the highest/lowest value for the objective function, i.e. are the fittest, are selected for the reproduction. In the reproduction phase, a new population is created by using the chromosomes of the previously fittest solutions. This cycle is repeated through a number of generations until some conditions are satisfied or for a certain amount of time (Yi & Malkawi 2009). The GA process is presented in Figure 2.

When creating a new set of population, the algorithm can introduce operators borrowed from natural genetics, such as mutation. Mutation randomly changes values of some chromosomes in some of the member of new population. Mutation is introduced as mutation rate which states the share of maximum number of mutated values in one solution. The GA prefers the better performing individuals by nature and drives the solution towards optimal solution which has most characteristics from the previously fittest solutions.

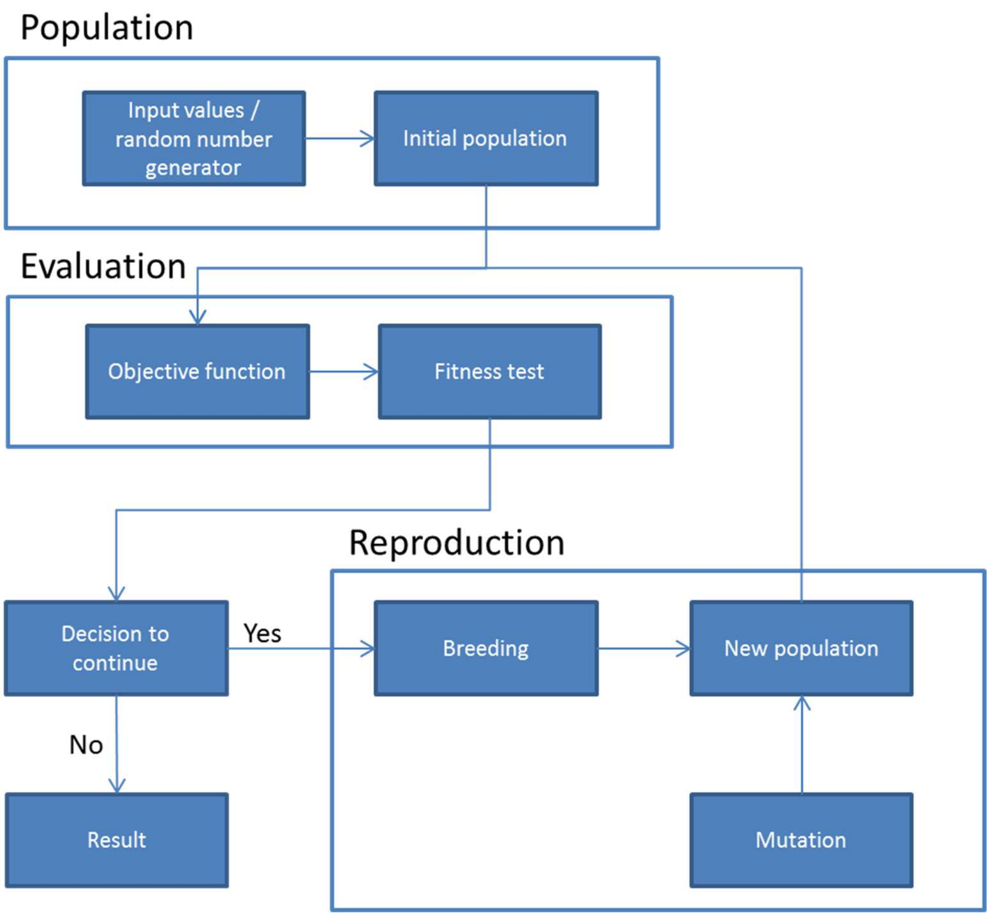


Figure 2 Genetic algorithm process (Yi & Malkawi 2009)

2.2.2 Genetic algorithm in building simulation

In building simulation using genetic algorithm, each solution of the population is a chromosome string of data consisting the values of each decision variable and gives value to the fitness function. Fitness function can be such as that of 'annual specific energy consumption'. Each variable represents one gene in the chromosome and values for each gene is restricted based on the optimization constraints. The chromosome string for one solution is represented in Figure 3.

	Building 1								Building 2								Building 3							
Despcrition of value	Location: X	Location: Y	Shape	Lx	Ly	w	Orientation	Nro of floors	Location: X	Location: Y	Shape	Lx	Ly	w	Orientation	Nro of floors	Location: X	Location: Y	Shape	Lx	Ly	w	Orientation	Nro of floors
Solution	7,6	-7,0	1,0	7,8	8,1	5,3	177	5	9,8	6,8	2,0	7,6	7,8	3,9	168	1	-6,5	-5,4	1,0	9,6	8,4	5,2	169	8

Figure 3 Chromosome string of one optimization solution in GA

Values of the solutions are mixed in the reproduction phase with breeding and mutation. When two solutions are bred, their chromosomes are cut in two and the ends are switched form a set of two new solutions. Mutation randomly changes values within a solution.

Formation of the solutions plays an important role in how simulation proceeds. If the values are building after building, the breeding phase is likely to change all values of certain building. If the values are set by feature, e.g. orientation, the change in breeding is rather likely to happen on certain feature on every building. This can be steered with mutation as mutation randomly changes values of genes.

2.2.3 Theoretical content of building optimization model

In this section, all the theoretical content and mathematical equations used in the optimization model are presented. Different parts are separated with underlined headings. The building energy consumption model is based on (Finnish Ministry of the Environment 2012a) and (Finnish Ministry of the Environment 2012b). Calculation of solar angle and energy production is based on (Benghanem 2011) and (Finnish Ministry of the Environment 2012b)

System boundaries

Defining system boundaries creates base for all optimization thus all the processes undergone within the system boundary. In building optimization system boundary is defined based on the studied entity and processes consists usually from energy and material flows (Kurnitski 2013).

Location-based data

Location-based data in building optimization consists from features outside the boundaries, e.g. weather and building restrictions. Optimization environment data ties the optimization model to a certain location or environment in which the model is performing the optimization process. Location-based data is indifferent from the optimization model, yet it affects the outcome of the results. For example, the energy optimization done in colder climates found significantly higher savings in energy costs than in warmer climates (Nguyen et al. 2014).

Building structure related units

Buildings are measured with several different units to measure their performance. Building envelope is measured based on geometrics and thermal properties. U-values measure the thermal transmittance of different parts of the building. Thermal transmittance measures how much energy is passed through the structure in respect of temperature and area of the structure and the unit of U-value is W/m^2K. U-values are usually given on roofs, walls, floors, windows and doors separately.

Windows are measured also with G-value. G-value measures the share of solar radiation the windows pass through. This affects the amount of solar gain, i.e. passive heat. G-value differs from zero to one where zero means that the window won't let any solar radiation through, i.e. no solar gain and one means that the window let all radiation through and the maximizes the solar gain.

Air tightness of the building shell is measured with air leak coefficient. Air leak coefficient is presented in the unit of 1/h and measures the ratio leaked air volume to total air volume of the building in one hour.

Building system related units

Building systems include HVAC-systems and other systems which participate in indoor climate. Amount of ventilation required is expressed as the ventilation rate. Ventilation rate is usually expressed by rate of how many times the whole air volume needs to change in one hour and the unit is 1/h. Ventilation rate can also be expressed in the unit of $dm^3/s/m^2$. Ventilation of 2/h corresponds to a value of 1,5 $dm^3/s/m^2$ when the average floor to roof height is 2,5m.

Heat recovery system is integrated into the ventilation system and recovers heat energy from exhaust air. The efficiency of heat recovery system is presented as percentage share of how much energy can be recovered.

Some building related systems produce excess heat during use. Such systems, e.g. lighting, can produce significant amounts of free heat which effect the use of other systems. The amount of free heat is approximated in respect of building floor area and the specific values for internal heat loads are presented in W/m².

Solar angles

For observing amount of direct solar irradiation to flat surface on hourly basis the solar angle of incidence needs to be defined hourly. In general form, angle of incidence coming to an angles surface is defined in formula 1.

$$\cos\theta_i = \sin s \sin\theta_z \cos(\gamma - \gamma_s) + \cos s\, cos\theta_z \qquad [1]$$

where θ is the angle of incidence, s is the slope of the surface, γ is the azimuth angle of the surface, γ_s is the azimuth angle of the sun and θ_z is the zenith angle of the sun.

Zenith angle measures the height of the sun from the horizon and it is defined as the angle between the sun and vertical normal of the earth. The value of zenith angle varies from 0° to 90°. Calculation of zenith angle is presented in formula 2.

$$\cos\theta_z = \sin\delta \sin\emptyset + \cos\emptyset \cos\delta \cos\omega \qquad [2]$$

where and θ_z is the zenith angle, δ is the declination angle, $\emptyset$ is the latitude and ω is the hour angle.

Declination angle δ measures the sun's position in respect to the equator plane. Declination angle varies throughout the year and can be defined with formula 3.

$$\delta = 23{,}45° \sin(360\ \tfrac{284+n}{365}) \qquad [3]$$

where *n* is the number of the day counted from the beginning of the year: January 1st is 1 and December 31st is 365.

The hour angle ω defines the orientation of the sun in respect of compass south. The value of the hour angle varies from -180° to 180°. Hour angle in the midday is 0°, negative values mean sun's orientation is eastward and positive values westward. Hour angle is calculated with formula 4.

$$\omega = 180° - 15° * h \qquad [4]$$

where ω is the hour angle and h is the hour of the clock from zero to twenty three.
Azimuth angle of the sun $\gamma_s$defines the difference from the sun's direction from compass south horizontally. Value of azimuth angle of the sun is zero when sun is directly in south, lesser than zero when the sun is in the east and greater than zero when the sun is in the west. Azimuth angle is calculated hourly and can be defined with formula 5.

$$\sin \gamma_s = \frac{\cos \delta \sin \omega}{\sin \theta_z} \quad [5]$$

where γ_s is azimuth angle of the sun is, δ is declination angle, ω is hour angle and θ_z is zenith angle.

Azimuth angle of the surface is set and is measured as the difference from compass south similarly as azimuth angle of the sun.

Energy production by using Photovoltaic

PV is included in the model as integrated area to the building façade. Building façade is defined as largest continuous surface pointing on general compass direction. This means every building has four facades: North, west, east and south.

Energy production is counted hourly on each façade with integrated PV. The amount of produced energy is calculated in respect of the total irradiation coming to the surface, area of the PV and efficiency of the PV and is calculated with formula 6.

$$P_{PV,h} = \eta \left(G_{b,T}\, H + G_{d,T}\right) A \quad [6]$$

where $P_{PV,h}$ is the energy produced during specific hour, η is the efficiency of the PV system, A is the area of the PV in m^2, $G_{b,T}$ direct radiation coming to the surface, H is the binary shading factor coming from the shading model and $G_{d,T}$ diffuse radiation coming to the surface.

Total irradiation coming to the surface is calculated as a sum of direct radiation $G_{b,T}$ and diffuse radiation $G_{d,T}$ coming to the surface. Absolute values for direct normal radiation $G_{b,n}$ and diffuse horizontal $G_{d,H}$ are received from the hourly weather data. Amount of direct beam radiation coming to the surface is calculated with formula 7,

$$\mathrm{G_{b,T}} = \cos \theta_i \; \mathrm{G_{b,n}} \quad [7]$$

where θ_i is the angle of incidence on specific hour.

Diffuse radiation is assumed as isotropic, meaning it comes evenly from every direction, and the amount of diffuse radiation is calculated with formula 8.

$$G_{d,T} = F\, G_{d,H} \quad [8]$$

where $G_{d,T}$ is diffuse radiation coming to the surface, F is the view factor $G_{d,H}$ is diffuse horizontal. View factor F is calculated with formula 9.

$$F = \frac{1+\cos s}{2} \quad [9]$$

Where s is the slope of the surface.

Reflected radiation is left out in this model, thus creating a model to notice reflectance from other buildings was too complex to create with resources allocated in this thesis.

Passive heating: Solar gain from the windows

Solar gain from windows represents the amount of direct solar irradiation coming in from the building windows. Solar gain is calculated separately in every general direction of the building. Total solar gain is depending on window area on every side of the building, direct solar irradiation and g-value of windows, which is defined in building regulations. The amount of direct solar irradiation is calculated in the same way as for PV considering the orientation of each building side differently. The amount of solar gain from one direction during one hour is calculated with formula 10.

$$P_{W,i,h} = A_i \, G_{d,T,i} \, g \, H \qquad [10]$$

where $P_{W,i,h}$ is the amount of heat coming through the window inside the building during hour h from direction i, A_i is the area of windows facing the direction i, g is the g value of the windows and H is the binary shading factor from the shading model.

Orientation and rotation geometry

Rotation of an individual building is defined by moving its corner points around the center point of the building counterclockwise on a constant radius. Coordinates of the building center point are defined as optimization variables. The coordinates of the corner points and turning radius of each corner is defined with the building shape and building parameters L1, L2 and w, which are optimization variables. Change in coordinates of one corner point is defined with formulas 11 and 12.

$$x' = x\cos\theta \; - y\sin\theta \qquad [11]$$
$$y' = x\sin\theta + y\cos\theta \qquad [12]$$

where x' and y' are the coordinate values after the rotation, x and y are the coordinate values before the rotation and θ is the angle of rotation.

When all the corner points are rotated around the same point simultaneously on their specific distances in respect of the rotation variable, the building orientation changes. Thus, the building turn counterclockwise, the true compass orientation of the building is calculated by subtracting the value of orientation value from 360°.

Shading model geometry

The shading model was developed based on the needs of the model and it defines if another building is blocking the direct view of the sun in respect of building central point and the length of the shadow covers the building center point. Shading model measures two different factors, direct view of sun and length of shadow of other buildings, and gives the binary shading factor, H.

Direct view of sun measures what angles are blocked from direct view in the horizontal plane. View is measured from buildings center point to all corner points of other buildings. Blocked view angles are defined separated from each adjacent building and the blocked angles are decided between the greatest and lowest values from the building corner based inspection. Length of shadow of other buildings calculates the length of building's shadow with respect to building height and zenith angle. Shading angles between two buildings are demonstrated in Figure 4.

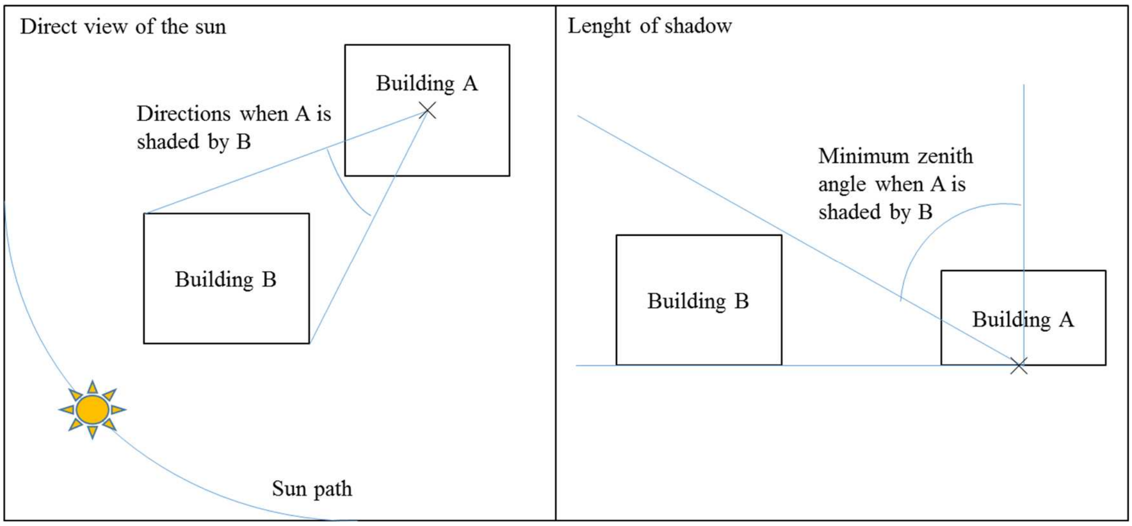


Figure 4 Shading angles between two buildings

Both factors are inspected hourly and per building and when the view is blocked and the length of the other building's shadow exceeds the distance between building center points, shading factor h is given a value of zero and building is considered shaded. Value of zero negates the effects of direct solar radiation coming to the surface in the calculations. If both conditions are no satisfied, the value of H is one and direct solar radiation is included in the calculations.

<u>Building energy consumption</u>

Building consumes energy only in form of electricity in the model. Electricity demand can be separated into three different streams: heating, cooling and electricity for appliances and lighting.

Model neglects the possibility for simultaneous heating and cooling used for space heating. The demand for heating and cooling is calculated from the energy balance. The model calculates the demand of heating/cooling energy based on the total energy needed for keeping the building on constant temperature subtracted with internal heating loads. Internal heating loads include passive heating, i.e. solar gain from windows and free heat, which consists heat loads from lighting, appliances and people. If the need for heat is negative, it is considered as cooling demand. Energy needed for hot water is separated from the energy needed for space heating and cooling and is estimated based on building floor area.

<u>Energy losses from conduction, ventilation and air leaks</u>

The amount of heating energy needed for keeping the building at constant temperature is calculated on hourly based and depends on the properties of building envelope, demand for ventilation and outside temperature.

Heat loss from the building envelope through conduction is based on the U-values of the building structures and the outsides temperature on current hour. U-values for building structures are set in the building regulations as minimum values. For each building, a total heat loss factor can be calculated from the U-values of different building parts and areas of respective building area. U-values and their respective areas are different for ground floor, roof, walls, windows and doors. Total heat loss factor is building specific value and gives the demand for heat on current hour when multiplied with the subtraction of set inside temperature and outside temperature from weather data. Calculation of heat loss from conduction presented in formula 13.

$$Q_{cond} = (T_{in} - T_{out}) R_{total}$$
$$= (T_{in} - T_{out}) (R_{wall}A_{wall} + R_{roof}A_{roof} + R_{floor}A_{floor} + R_{windows}A_{windows}) \quad [13]$$

Heat needed for ventilation/cooling is calculated from the ventilation rate, efficiency of heat recovery and temperature difference of set inside temperature and outside temperature. Ventilation rate is decided base on the building type and is collected from the building regulations. To calculate the heat demand for ventilation the ventilation rate is multiplied by building volume, the temperature difference of set inside temperature and outside temperature and heat recovery factor. Heat recovery factor is calculated as the share after utilization of heat recovery system that works in the efficiency ε, which is collected from the building regulations. Hourly heat energy demand of ventilation system formula is presented in formula 14.

$$Q_{vent} = V_{vent} (T_{in} - T_{out}) c_{air} \rho_{air} (1 - \varepsilon) \quad [14]$$

where V_{vent} is the volume of required air flow, T_{in} is the set inside temperature, T_{out} is outside temperature on a current hour from the weather data, c_{air} is heat capacity of air, ρ_{air} is density of air and ε is the efficiency of heat recovery system.

Volume of required air flow is calculated with ventilation rate collected from building regulations, building volume and floor area.

Heat loss from air leaks is calculated with the air leak coefficient, building volume, building floor area and the temperature difference of set inside temperature and outside temperature. Air leak coefficient collected from building regulations and is based on the building type. Hourly heat energy demand to match the air leaks is calculated with formula 15.

$$Q_{air\ leaks} = V_{air\ leak} (T_{in} - T_{out}) c_{air} \rho_{air} \quad [15]$$

where $V_{air\ leak}$ is the total volume of air leaks.

Free heat

Free heat includes internal heat loads coming from people, lighting and appliances. Values of internal loads are based on building floor area and specific values are collected from building regulation based on building type.

Building space heating/cooling energy demand

Building's demand for heating/cooling energy for maintaining the building at a constant temperature is calculated based on heat losses and internal loads. Heat losses include heat losses from conduction, air leaks and ventilation. Internal loads include free heat from people, lighting and appliances and solar gain from windows. If the total amount of energy is positive, it is considered as the demand for heating and if negative, it is considered as cooling demand. Calculation of space heating/cooling energy demand is presented in formula 16.

$$Q_{space} = Q_{air\ leaks} + Q_{cond} + Q_{vent} - Q_{internal} - P_{W,i,h} \quad [16]$$

Domestic hot water

Domestic hot water requires electricity during the active hours of the building and is irrelevant of the heat/cooling demand needed to maintain the inside temperature of the building constant. Need for domestic hot water is estimated from the building floor area and specific domestic hot water need is collected from building regulations.

Building electricity consumption

Total electricity demand of the building is calculated as a sum of energy need of building systems multiplied by their respective efficiency. Model neglects the possibility to have simultaneous heating and cooling demand and the demand for cooling is defined as hours when demand for space heating energy is negative. Calculation of total energy demand is presented in formula 17.

$$P_{elec} = \eta_{elec.heat} Q_{space,heat} + \eta_{cooling} Q_{space,cool} + \eta_{elec.heat} Q_{DHT} + P_{light} + P_{appl} \quad [17]$$

3 Methodology

This section presents the construction of the optimization model used in this study and defines the restrictions of separate features in the model.

3.1 Limitations of the study

Limitations considering the optimization model needed to be made in respect to resources allocated in this thesis. The optimization model has been designed simple yet correspondent to other smaller optimization studies. Some parts of different features, such as shadowing, have been simplified and averaged in terms of probable accuracy. Energy consumption model does not calculate for example all possible heat losses: heat losses from heat bridges were left out as the creation of calculation model was considered too time-consuming compared to significance of the possible output. The model considers only the import and export energy costs and does not calculate the cost of construction or used technology features, such as photovoltaic (PV) or heating and cooling system. Energy costs are introduced to the model to define relative benefit from the on-site production and the costs are not comparable between different locations. Limitations and simplified features are reviewed in the discussion as the variation in results between cases with different input variables and restrictions. The results are reviewed against other studies concentrated on the feature under evaluation.

3.2 Optimization boundaries

In this thesis, the system boundary is set around the site where the buildings are located and electricity as the only possible form of distributed energy. Electricity inside boundary can flow freely between buildings. The model accounts only for the import and export flows of electricity as the only possible external energy flow. Restricting the energy flows only to one makes the optimization model simple and examination of energy flows unambiguous within the same optimization environment. The model is not suitable for comparing absolute energy flows when the optimization environment is different. System boundaries are presented in Figure 5.

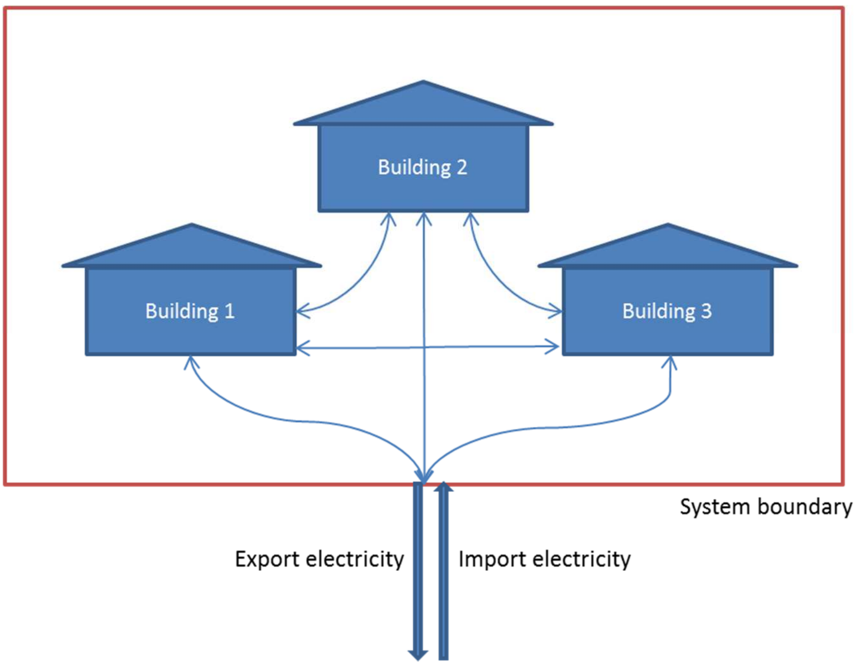


Figure 5 Optimization system boundary

3.3 Optimization model

The optimization model works in calculation steps and each step has been implemented on separate Excel spreadsheet. Each spreadsheet takes figures, performs calculation and returns the answers to main spreadsheet. Some of the spreadsheets are linked directly thus they calculate only partial results. This kind of structure makes the development of separate features, e.g. shadowing, possible within the optimization model easy. The structure of the model is presented in Figure 6 and specifications of different features of are described in the following paragraphs.

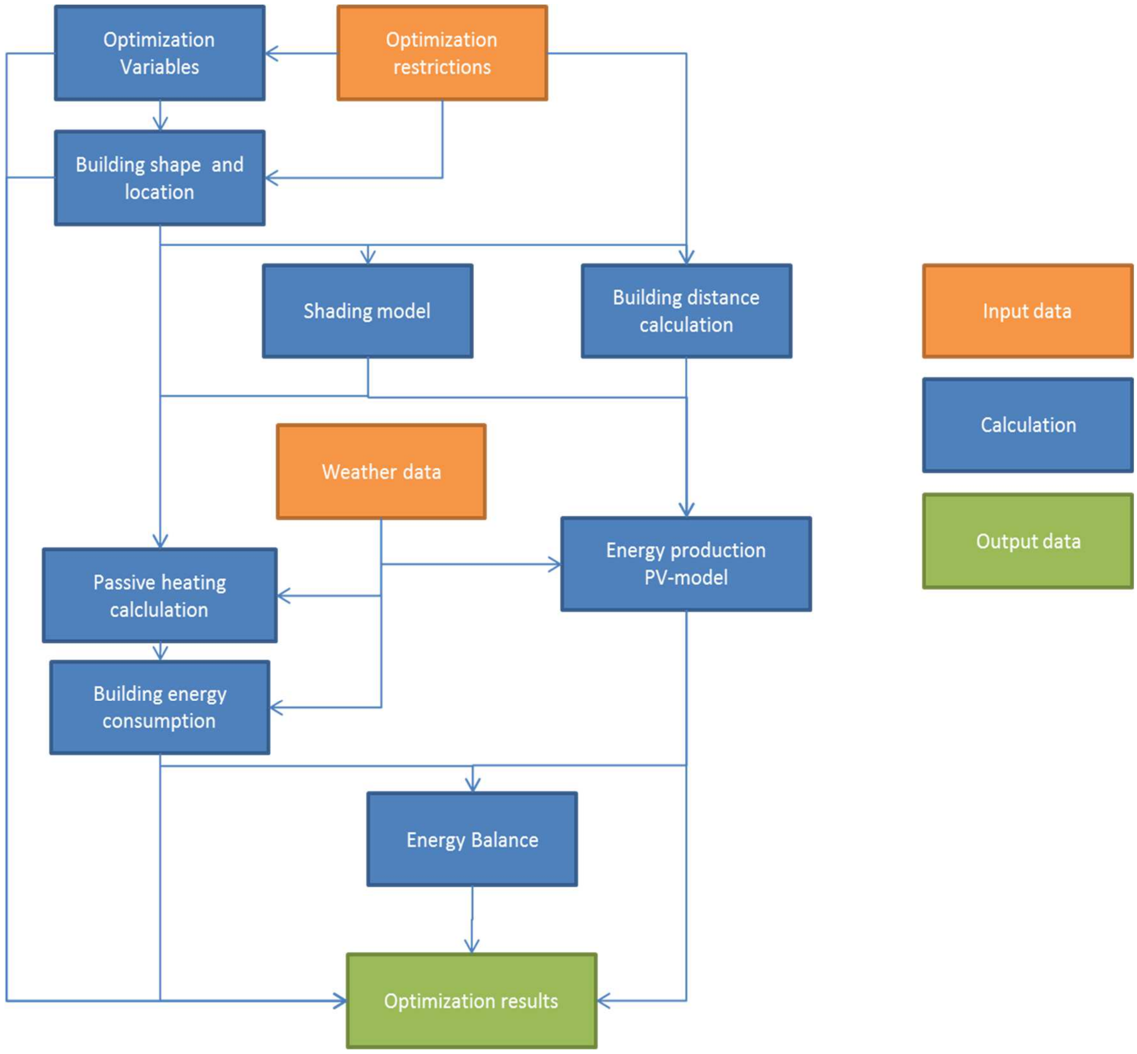


Figure 6 **Optimization model structure**

3.4 Optimization process

The optimization process starts with input values that can be any values within the given constraints. The GA can find a feasible solution with values that does not fill the constraints, but giving a set of feasible starting values makes the optimization process significantly faster. After the input values are given, the model calculates the value for the fitness function and the GA engine can start. The GA will stop when no improvement for the fitness function is found in the given maximum time. The result from the GA can then be directly accepted as the final result or GA can be run again or it can be manually iterated before running the GA again. Optimization process is presented in Figure 7. Process enables the user to use the model purely as a mathematical approach to find the best solution or to manually process the result by iteration.

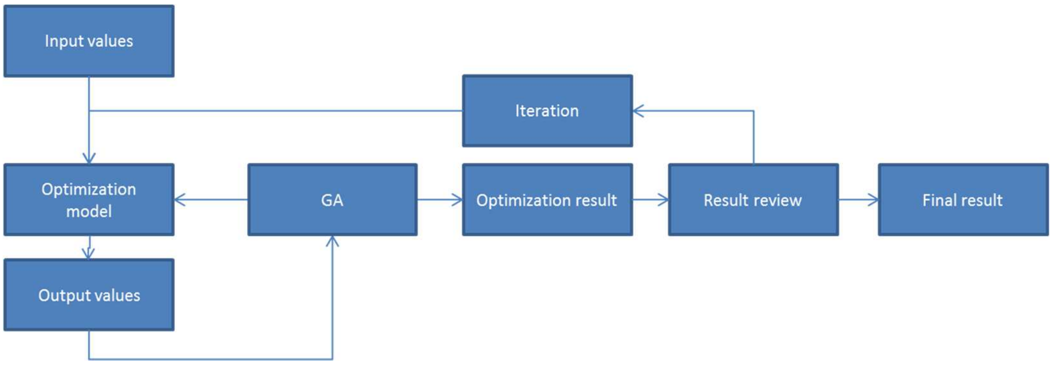


Figure 7 Optimization process

3.5 Optimization variables

Optimization operates with multiple discrete and continuous variables for each building.

<u>Building location, shape and orientation</u>

Location of the building is determined by two continuous and restricted variables that decide the center point of the building footprint. The constraint set for the center point of the building allows for drawing the boundary lines for the viable building zone. Building shape is decided by one discrete variable that chooses one of the predetermined and parameterized shapes. For this optimization problem, there are five predetermined shapes including rectangular, L-shape, T-shape, U-shape and O-shape.

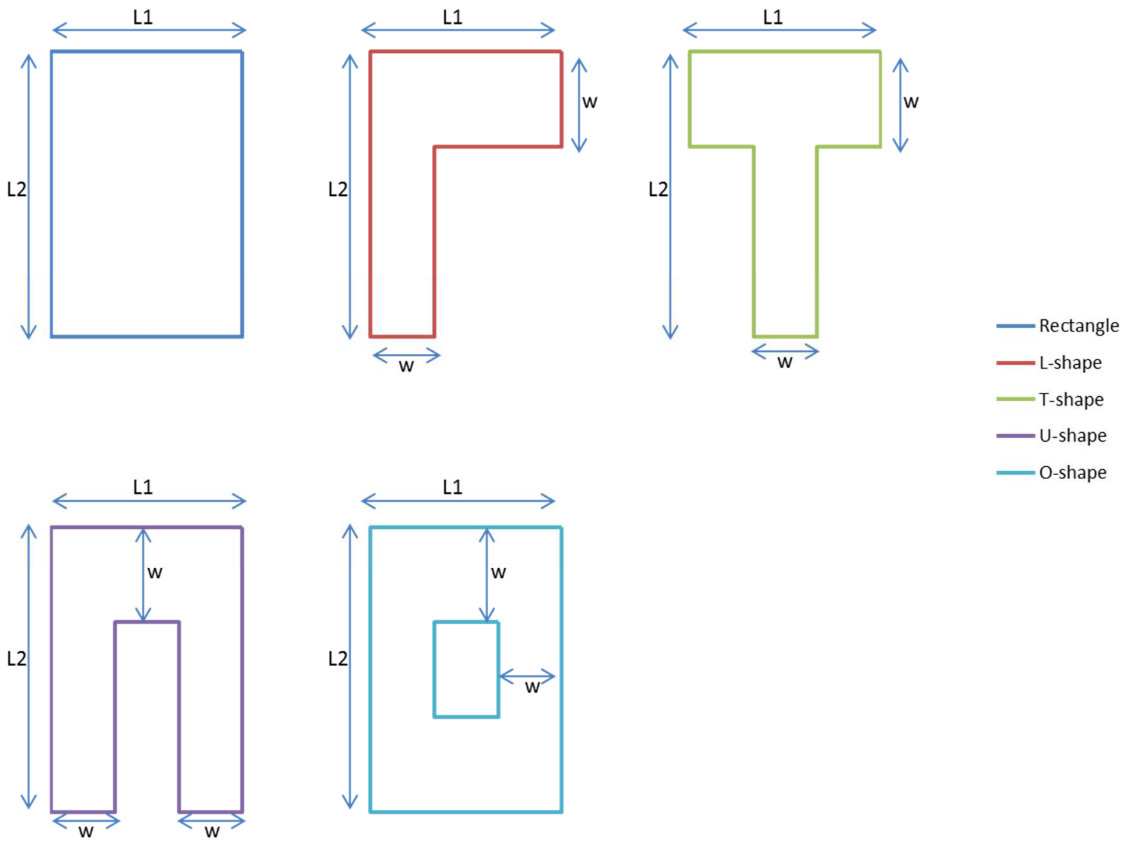
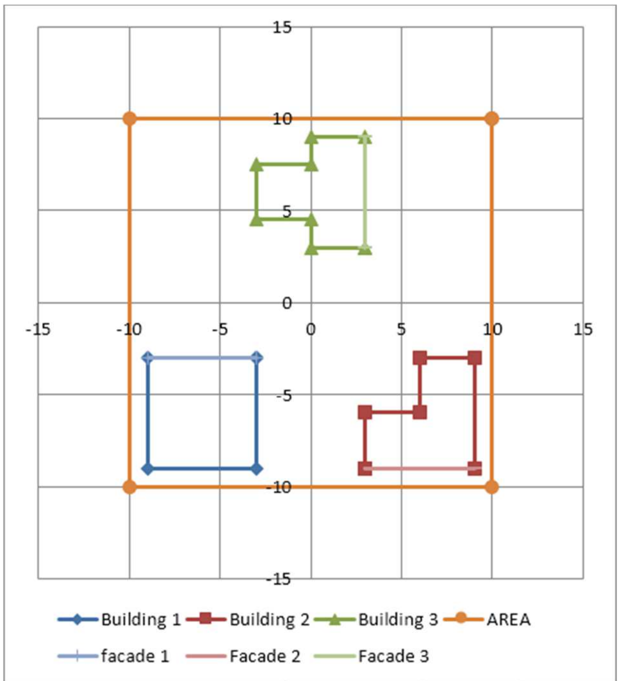


Figure 8 Parametrization of building shapes

The dimension of the building and its shape are calculated with three continuous and restricted dimension parameters, which are named L1, L2 and w. Corner points are calculated with these three parameters in respect of the building center point. The parametrization is displayed in Figure 8.

The dimension parameters L1 and L2 are restricted to be greater than 6 meters. Parameter w is restricted to be greater than 3. This boundary makes minimum corridor width to be 3 meters. In some shapes, the ratio of w to L1 and w to L2 are penalty restricted in case of unfeasible shapes. Penalty constraint means setting a significantly high penalty on breaking a limit, which is in this case that ratio of w to L1 or w to L2 needs to lower than 0,5 in shape O and U. If the ratio would be higher building envelope would be twisted inside out in some parts of the building. Building height is chosen by the optimization model based on discrete floor number variable which is restricted between 1 to 10 floors. The floor to ceiling height is fixed for all floors.

Building orientation can be changed through the rotation parameter restricted from 0 to 360 degrees. The orientation variable rotates the corner points of the building around the decided center point of the building counter clock-wise. With the rotation feature, there are two different compass orientations: Building orientation and compass orientation. Building orientation always refers to the setup before the orientation feature. True compass orientation, i.e. the direction of building north in relation to true north, refers to the situation after the orientation feature and is calculated by decreasing the value of orientation variable from 360 degrees. As an example, building north façade is facing compass north when the building orientation parameter is 0. When the orientation parameter of the building is 180 degrees, the building north façade is facing compass south. The building orientation is demonstrated in Figure 9 and the building north façade is highlighted in the illustration.



Building	1	2	3
Orientation variable	0	180	270
Compass orientation	0	180	90
Facade directino	north	south	east

Figure 9 Building orientation

3.6 Fixed variables

Optimization includes a number of fixed variables that can be changed depending on the designed location, technology and case under research.

Window to wall ratio on each facade
The window to wall ratio on each façade is one of the research subjects and thus fixed and varies depending on the case. This decision makes the optimization engine to find the optimum size, location and shape of the building based on the percentage of window surface on each side of the building.

Façade BIPV area and orientation
Every building can have one or two facades with photovoltaic (PV) panels. If the building has one façade of PV panels, panels are located on the building north façade. This leads to that building orientation will also tell the compass orientation of the main PV-façade. Buildings that have two facades equipped with PV, panels are located on the building north and building west facades.

PV facades are highlighted in the illustrations. Illustration of highlighted facades with PV integration are presented in Figure 10.

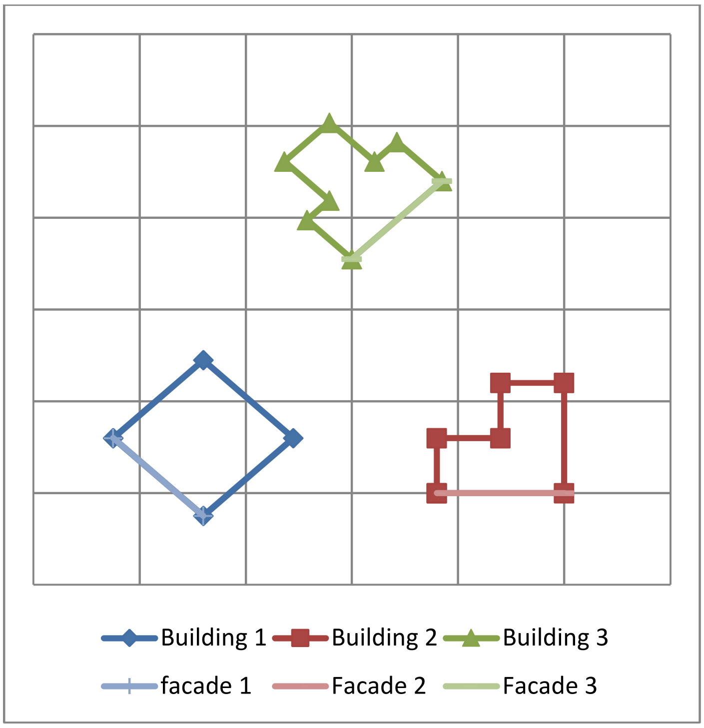


Figure 10 Highlighted facades

The maximum amount of PV is restricted on each façade in respect of the façade size, floor height and amount of window surface on current façade. Regarding the feasibility, PV-panels cannot be located on the facade of the first floor. This means that buildings with only one floor (ground floor) do not have any energy production. The PV-area for each façade is thus calculated as the area of façade excluding the first floor subtracted by the minimum window area on that façade. The optimization model is flexible to include or exclude many facades and/or roof with PV panels based on the selected objective function.

Number of buildings
Practically, the optimization model is designed with utmost flexibility in optimizing as many buildings as is desired. In these simulations, the number of buildings is fixed in three and five buildings. In the first phases, tests were made with building number varying from two to five buildings. The decision to proceed with a minimum of three buildings was made because this was the smallest amount of buildings where interaction between buildings can be seen and studied in detail. A small number of buildings leads to lighter optimization model and shorter optimization time, which is one of the desired requirements. To see how the model performs with a higher amount of buildings and see how the amount of buildings affects the behavior of the model additional case was made with five buildings.

3.7 Other constraints

The optimization model does not include self-shading of buildings. Model for self-shading was left out thus the façade PV is located on the sides which do not have self-shading in buildings with one façade PV. Preliminary results also indicated that shapes with high self-shading (shapes H and O) were not chosen as a solution by the optimization model. Based on these observations, the self-shading feature was not created in boundaries of this thesis.

Total floor area was restricted to have a minimum value of 1000 m^2 on three building cases and 1200 m^2 on five building cases in respect of primary assumption that smaller floor area will be the most efficient. One-sided constraint leaves room for the possibility that the model finds a solution where increased floor area enables more wall area and therefore more PV-façade, i.e. energy production.

3.8 Distances between buildings

Minimum distance between buildings is set as 4 meters. The distance between buildings is measured from eight different points on every building with respect to similar points on all other buildings. The points are defined from the center point of the building and the distance parameters. These eight points create the building area that might differ from the exact building footprint depending on the building shape. The four corner points of building area are determined same as the corners of the rectangular building. Other four building area points are located at the middle of each pair of corner points. This definition makes it possible for distance between buildings to be less than four meters as the constrained area is defined from certain number of points and not from continuous area. Thus, the viable building zone is restricted to an area of 10 x 10 meters in three building cases and 15 x 15 meters in five building cases, three distance checkpoints on each building side are considered sufficient. Adding extra checkpoints will be required if the suitable building area is increased.

3.9 Shading model

The shading model calculates if the building is shaded by other buildings and takes out the amount of direct solar radiation available for PV and passive heating on considered hour. The shading parameter is considered binary and it is calculated separately on each building to every other building. The building is considered shaded if the direct vision of the sun towards buildings center point is blocked by another building horizontally and another buildings shadow is higher than the average height above the ground floor on a distance between building calculated on part building distances. When shaded, the building does not get any direct solar radiation.

Shading model affects effectively on morning and evening sun since the shadows are then long and solar panels installed only on buildings vertical facade.

3.10 Building energy model

The building energy model is mainly based on the energy calculation method presented in Finnish building regulations parts D3 (Finnish Ministry of the Environment 2012a) and D5 (Finnish Ministry of the Environment 2012b) yet the method has been expanded for hourly energy consumption and production. The energy production has been specified from monthly averages to hourly model that uses measured hourly weather data from predetermined locations.

3.10.1 Weather data

Optimization model uses hourly weather data from one year and compresses it to twelve days each representing the average of one calendar month. Compressing is done directly by calculating the average values for each hour on certain calendar month. The model utilizes values for temperature, direct solar radiation and diffuse horizontal radiation information from the weather data. The compressed weather data simulates the average weather of the target location including seasonal changes in temperature and solar radiation.

Hourly weather data was used for two geographical locations of Helsinki, Finland available from the Finnish meteorological institute for the year 2012 and the weather data for Bucharest, Romania is applied from ASHRAE 2011.

3.10.2 Energy production: Building integrated PV model

BIPV was chosen to the onsite energy production for the model as the area for façade integrated PV is dependent of façade area and further on the building shape and orientation. By choosing BIPV as the onsite production, the model must balance the energy consumption and production in terms of building shape, orientation and dimension, which are all optimization variables. BIPV also interacts with the windows’ solar gain.

PV model calculates the total solar irradiation to the façade with BIPV. The angle of incidence is calculated on every day and hour separately based on the weather information and solar angles. Diffuse radiation is considered as isotropic, and the calculated view factor is 0,5 for vertical surfaces. Efficiency for the PV system is set as 14 % which represents the efficiency of average commercial system (ISE 2013)

3.10.3 Energy consumption

Hourly energy consumption model calculates the heat loss from the ventilation and the building shell based on the Finnish building regulations D3 (Finnish Ministry of the Environment 2012a)and D5 (Finnish Ministry of the Environment 2012b). Need for domestic hot water is estimated from the building area based on D5. Heat values for free heat including people (5 W/m²), lighting (12 W/m²) and appliances (12 W/m²) are also from D3 and D5. Free heat generation is considered during normal office hours, from 7 am to 5 pm. Buildings are considered to have electric space heating and domestic hot water is heated with electricity on demand.

Passive heating through windows

Passive heating through windows is calculated from the amount of direct solar radiation on each façade. Calculations use the same solar angle of incidence than in the BIPV calculations. The amount of passive heating is calculated from the irradiation on every building façade in the four main directions and based on the window area on each direction. Window properties are based on building regulations of observed locations.

Electricity demand of the building

To calculate the building demand for heating electricity the model sums the heating energy demand subtracted by the free heat and passive heating. When positive, the building needs heat and demands electricity based on the efficiency of its electrical heating system which is 1 (Finnish Ministry of the Environment 2012a). When the heat demand is negative it is considered as cooling demand. The model assumes that building has an average efficiency free cooling device and the electricity demand is based on the cooling factor of 2.5 (Finnish Ministry of the Environment 2012b). Model does not take into account the electricity demand of HVAC fans and pumps, thus measurement of such features is based on a higher level of detail of the used technology.

Buildings also consume electricity for lighting and appliances. The electricity consumption of lighting is 21 W/m² based on D5 and 12 W/ m² for appliances which match the amount of free heat gained (Finnish Ministry of the Environment 2012b).

The given efficiency and cooling factor can be altered to match any regulations or technologies available. The used values for building envelope and building operational parameter are presented in Table 1.

Table 1 Building envelope specification and building operational parameters

	Helsinki	*Bucharest*
Wall U-value [W/m²K]	0,17	0,61
Roof U-value [W/m²K]	0,09	0,33
Floor U-value [W/m²K]	0,16	0,64
Window U-value [W/m²K]	1	1,3
Window G-value	0,675	0,675
Door U-value [W/m²K]	1	1,3
Heat recovery	0,5	0,5
Ventilation rate [dm³/s/m²]	1,5(1	1,5(1
Air leak coefficient [1/h]	2	2
Lighting power [W/m²]	21	21
Appliances [W/m²]	12	12
Time of use for lighting and appliances	07:00 - 17:00	07:00 - 17:00

1) Corresponds to ventilation rate of ~2 / h, when floor to roof height is 2,5 m.

3.10.4 Energy Sharing

Buildings that have electricity production can share excess electricity to other buildings. The amount of excess electricity is calculated from the difference of electricity production and consumption for each building separately. If the amount of excess electricity is higher than the total electricity deficit of other buildings, it can be sold as surplus energy to the grid.

Passive heating cannot be transferred from one building as heating energy. The model calculates first the demand for cooling and the electricity needed for cooling is included in the electricity demand of the building, which is taken into account when calculating the amount of excess electricity.

3.10.5 Energy costs

Energy costs can be set freely and the only meaningful attribute for the energy prices is the ratio between sellable surplus electricity to the price if bought electricity for direct consumption. This is because there are no other costs related to the optimization and thus the set surplus energy compensation and electricity cost affect only the most favorable way of energy use. As mentioned the in the previous chapter, the ratio between surplus compensation and bought electricity is 0.5 meaning that producing for self-use is twice as beneficial as to produce extra.

3.10.6 Energy balance

Energy balance is calculated as total energy consumption of all buildings on certain hour subtracted by the total production of energy from all buildings on considered hour. The model encourages multiple buildings to cover the energy consumption throughout the day rather than maximize energy production of one building. This is achieved through adjusting the surplus energy price to be significantly lower than the price of self-use. The price of surplus energy is half of the price of the purchased energy. This resembles the current market situation as the electricity consumer pays the transmission and distribution fees which make the bought electricity more expensive than sold surplus energy (EIA 2015).

3.10.7 Fitness function

The fitness function is the objective function which the optimization model aims to minimize or maximize. In this model the fitness function is the total export energy cost subtracted with the import energy compensation and the model aims to minimize the costs.

3.11 Cases

The optimization model was tested with different cases to see how the model reacts to different weights on fixed variables. Most important fixed variables were the ratio of window surface on four main directions and number of facades with PV. All case specific variables are presented in Table 2.

All the cases are tested in two locations: cold climate (Helsinki) and hot climate (Bucharest).

Case 1 can be held as the baseline case. The baseline case has BIPV on every building in the building’s north façade. The window areas are set to 10 % of the wall area on every major direction. This case acts as the baseline case and demonstrates the assumed default parameters.

Case 2 aims to balance the passive heating and electricity production. In case 2, facades on both sides of the PV-facade have increased window area. These facades have the most possibility to gather passive heating yet they have higher heat loss. The south and north façade have 10 % window area when east and west facades have 30 % window area.

In case 3, every building has two BIPV facades on two adjacent facades. In this case, the tested property is how the model sets up the BIPV-facades when surplus production is highly expected.

Case 4 is final tested case with three buildings and was created to confirm that the model for passive heating works as presumed: The effect of passive heating gathers heat and the most windows face southwards in cold climate and northwards in a hot climate to minimize the effect of passive heating. The building north façade with the highest number of windows is highlighted in the illustrations.

Case 5 is to test the scalability of the optimization model and two extra buildings were introduced to the model compared to previous cases. This was tested with the same constraint as case 2: Each building has one PV façade, 10 % window area on north and south facades and 30 % of window area on east and west facades. The suitable building area was increased to 15 times, 15 in respect to the increased building mass to have enough room the organize efficiently. Also, the constraint of minimum floor area was increased to 1200 m^2.

Table 2 Case specific variables

	Case 1	*Case 2*	*Case 3*	*Case 4*	*Case 5*
Suitable building zone	10 x 10	10 x 10	10 x 10	10 x 10	15 x 15
Minimum total building area	1000	1000	1000	1000	1200
Number of buildings	3	3	3	3	5
Number of PV-facades per building	1	1	2	0	1
Orientation of PV facade (in terms of building directions)	North	North	North, west	-	North
<u>Wall to window ratio</u>					
Building north facade	10 %	10 %	10 %	50 %	10 %
Building east facade	10 %	30 %	10 %	20 %	30 %
Building west facade	10 %	30 %	10 %	20 %	30 %
Building south facade	10 %	10 %	10 %	10 %	10 %

Optimization options were the same in all cases and locations. The options are presented in Table 3.

Table 3 Optimization options

Optimization option	*Value*
Convergence	0,0001
Mutation rate	0,3
Population size	200
Random seed	0
Maximum time without improvement [s]	300

3.12 Case comparison indicators

The cases are compared to each other with several different indicators. Indicators are separated into two categories: Basic and advanced indicators. Basic indicators can be defined directly from the results table and in this case comparison three different basic indicators were examined. First basic indicator is the energy costs of the tested time period. The costs are reviewed as separate buildings and as a group of buildings that can share produced energy. Second basic indicator is the ratio of renewable energy production to total energy consumption. The ratio of renewable production to total consumption describes the dimensioning of the renewable energy production Third basic indicator is the specific energy consumption of buildings separately and as a building mass.

Advanced indicators are collected from the different parts of the optimization models and compare more specific attributes of separate buildings and total building mass. First advanced indicator is onsite energy fraction (OEF). OEF describes the share of self-produced energy that is also self-used (Cao et al. 2014). This is calculated on separate buildings and on the building mass. Second advanced indicator is onsite energy matching (OEM). OEM describes the ratio of self-produced energy that is used on site to total self-produced energy (Cao et al. 2014). This is also calculated separately on each building and for the building mass. Third and fourth indirect indicators are the maximum hourly deficit and maximum hourly surplus. With these two indicators, benefits from energy sharing between multiple buildings compared to separate buildings in terms of needs for required power grid infrastructure (Ala-Juusela et al. 2015). Maximum deficit and surplus are calculated with and without a possibility to share energy.

4 Results

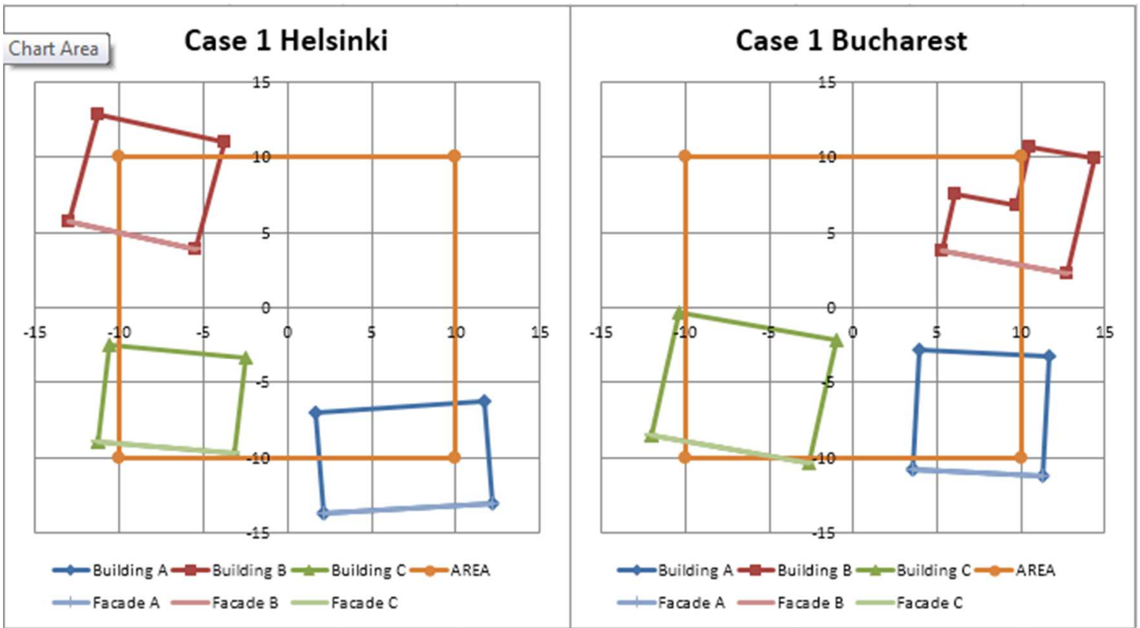
This section presents the optimization results from five cases presented in section 3.11. Detailed case results are presented in appendix 1. Detailed results include main information about the building and building mass, a simple mapping of the location, shape and orientation of the solution and energy production and consumption profiles. Cases are compared with case indicators presented in section 3.12. The case indicators are presented in appendix 2.

Section consists of two parts: Case comparison and location comparison. In case comparison, results are reviewed and compared case by case to see how different location based data affects the choices made by the model. Each case starts with figure presenting mapping of solutions with the number of floors and orientation as additional information. In location comparison, cases are reviewed with each other in same location.

4.1 Case comparison

In this section results are compared by case. Every case setup is reviewed based on results from the two defined locations, Helsinki and Bucharest. Goal of case comparison is to see how the model considers the different building regulations and climate, especially the amount solar irradiation and differing solar angles. The variables especially under review are building shape and orientation and OEM and OEF of different building compared to building mass.

4.1.1 Case 1: One PV facade, equal windows on every direction



Building	A	B	C	Building	A	B	C
Nro of floors	7	1	9	Nro of floors	5	1	8
PV orientation	176	194	185	PV orientation	183	192	191

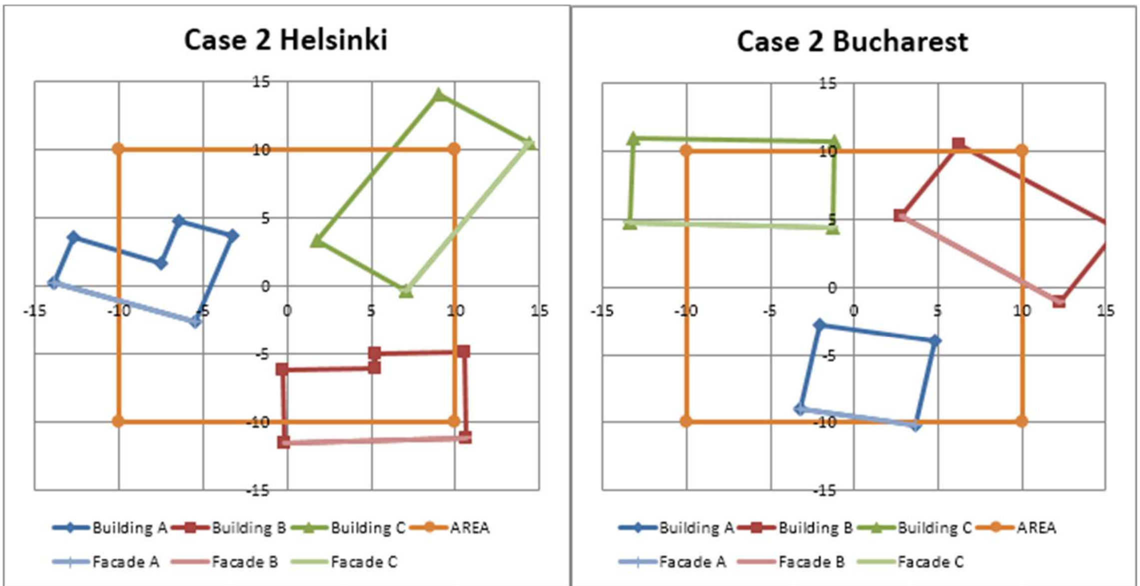
Figure 11 Mapping of results from case 1

Mapping of results for case 1 is presented in Figure 11. Results of case 1 for Helsinki use the rectangle shape for the building as also in Bucharest. Bucharest has one L-shape building but it responses only 4 % of the total area so its effect on the total energy consumption is small. The rectangle shape has the lowest ratio of building volume to total building area and is the most energy efficient shape available in the optimization thus the energy consumption model is dependent on the building volume. This can also be seen in the specific energy consumption as smaller values in larger buildings.

L-shape a has higher ratio of façade area to total building area when compared to the rectangular shape so it is efficient to decrease the energy efficiency in terms of consumption to gain higher production when the building regulations are highly demanding. Based on this, in case 1 the minimizing the energy consumption is more valuable than increasing the production. In other words, compensation from higher production is not economical with case 1 specific constraints and input variables.

The production is fitted to be completely utilized in the building itself and the OEM is 96 – 100 % in every building. This reinforces previous observation and the system has greatest economic benefit when it does not produce excess energy.

4.1.2 Case 2: One BIPV façade, extra window area on building east and west



Building	A	B	C	Building	A	B	C
Nro of floors	1	2	10	Nro of floors	1	7	6
PV orientation	199	179	124	PV orientation	190	214	182

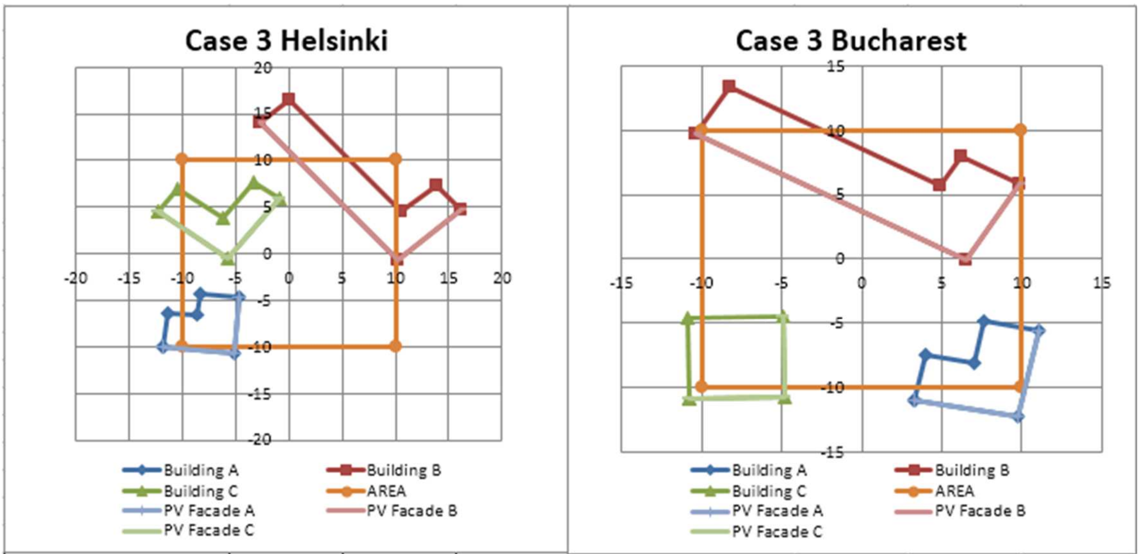
Figure 12 Mapping of results from case 2

In Case 2 extra windows are added to the both ends of the PV façade. Higher amount of window surface increases the free heat gained from the solar irradiation through the windows. Solar irradiation can generate extra cooling demand or it can be used to decrease the demand for heating electricity. Mapping of results for case 2 is presented in Figure 12.

Based on the building regulations it can be assumed that in Bucharest the effect of increased window area will be greater than in Helsinki. The results from Bucharest are concentrated to minimize the energy consumption as the buildings are all rectangles. Location and orientation in Helsinki support the scheme that every building tries to gather as much energy as possible for its PV façade and the PV façades are oriented like an arch. It can be interpreted as buildings A and C are covering one façade with larger window area (facades next to PV façade) from direct sunlight coming from low angles from the direction of west to southwest or east to southeast. Similar orientation is slightly available in the Bucharest case with the larger buildings B and C. This can be seen in the energy consumption curve of Helsinki building 3 in the daytime consumption of day 9, where the curve has a trough during the evening hours. This comes from decreased demand for cooling on the hour when the building is shaded during the sunset and the amount of direct radiation is the highest to the windows.

The OEM and OEF values do not show significant change between results with or without energy sharing. In Helsinki, the demand for import electricity has decreased only 0,2 % with energy sharing and most of the excess energy is unutilized. This may be a consequence from the highly characteristic energy consumption model. For example, the energy used for external loads starts and ends by a specific hour and the demand curve is very steep on these specific hours.

4.1.3 Case 3: Two PV facades, equal windows



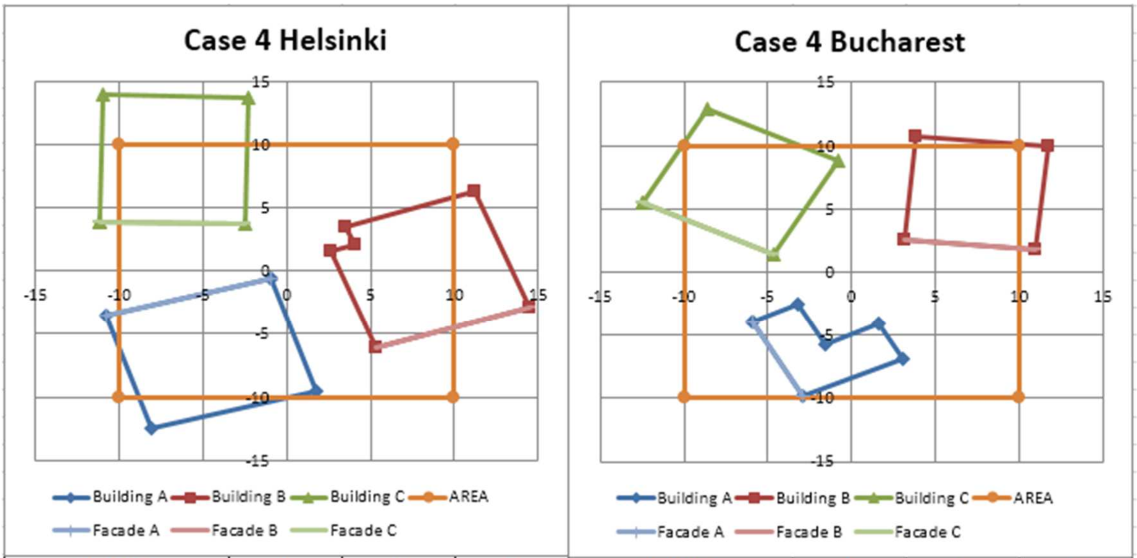
Building	A	B	C	Building	A	B	C
Nro of floors	3	10	1	Nro of floors	1	10	1
PV orientation	185/95	229/139	217/127	PV orientation	191/101	210/120	179/89

Figure 13 Mapping of results from case 3

Mapping of results for case 3 is presented in Figure 13. For both locations, similar features arise from the results. With two adjacent PV facades, both cases have concentrated the greatest part of the required building area in one large L-shaped building that covers 93 % of the required building floor area in Bucharest and 86 % in Helsinki. OEMs in these large buildings are 97,5 % in Bucharest and 93 % in Helsinki and OEF 28 % and 29 % respectively. In Bucharest, the other two buildings, A and C, are one-floor buildings and thus not have energy production based on the constraint that ground floor is not feasible for PV façade. In Helsinki, one of the small building, C, is one floor building and the other, building A, has three floors. The three-floor buildings OEM is 96 % and OEF 23 % which are almost the same as in the large building in same scenario.

When observed as a building mass, OEM in Bucharest has increased by 0,2 %. This point to that only small fraction of the excess energy can be used in other buildings and the possibilities for energy sharing are scarce. Same observations can be made from the results in Helsinki and only 2 % of the excess energy can be used in other buildings.

4.1.4 Case 4: No energy production, extra windows on building north, east and west.



Building	A	B	C	Building	A	B	C
Nro of floors	1	7	3	Nro of floors	1	7	7
PV orientation	343	161	181	PV orientation	242	183	207

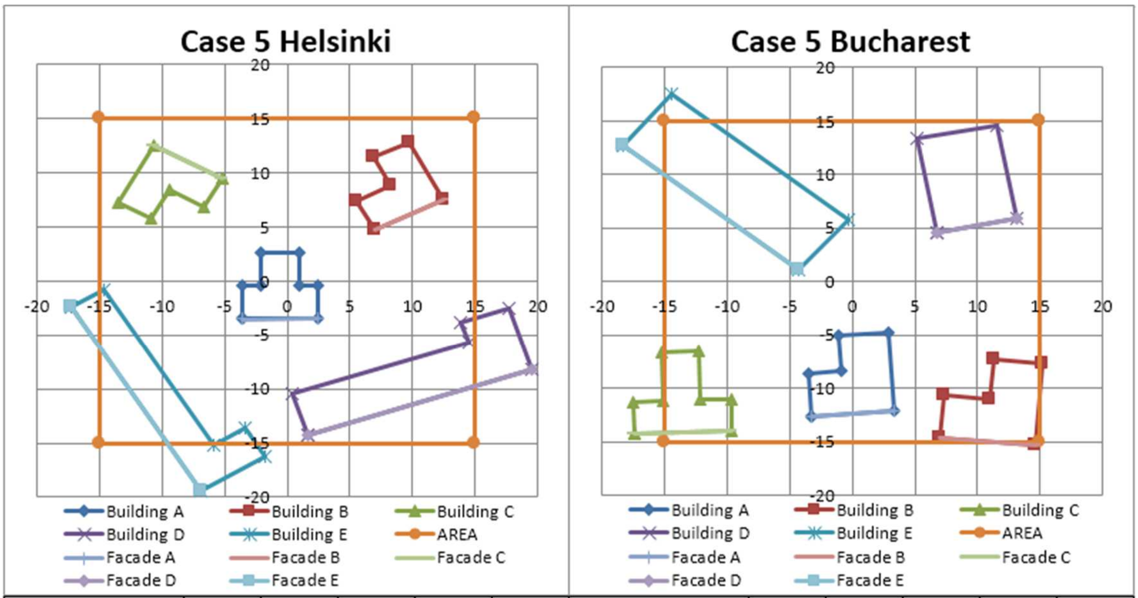
Figure 14 Mapping of results from case 4

Mapping of results from case 4 is presented in Figure 14. With no energy production, the model aims to find the combination of variables that achieves the most energy efficient setting and the results mirrors this assumption.

Building orientation and the specific energy consumption indicates that the building facing south has the smallest specific energy consumption. This indicates that the highlighted façade with 50 % of windows, i.e. the one deciding the orientation, is profitable to orient for collecting heat from solar gain as much as possible. This also indicates that heat demand is dominative to cooling demand. This is probably because the cooling system is more efficient than the heating system and thus the amount of electricity needed for cooling is lower in respect of total specific (heating or cooling) energy needed.

On both locations, one of the building is considerably smaller than the others. This building is building A in both locations. Helsinki building A has its window façade pointing almost directly to north and in Bucharest window façade of building A is towards west to southwest. This difference proposes that in Helsinki the simulation result might not be global optimum as the orientation differs radically from others.

4.1.5 Case 5: Testing the model with 5 buildings



Building	A	B	C	D	E
Nro of floors	1	1	1	10	4
PV orientation	180	153	29	161	239

Building	A	B	C	D	E
Nro of floors	1	1	1	3	8
PV orientation	176	185	16	169	220

Figure 15 Mapping of results from case 5

Model performed well with five buildings and optimization process was not significantly longer though the number of variables was increased by 66 %. Mapping of results from case 5 is presented in Figure 15.

Results show that with a larger number of buildings, designing the entity becomes more beneficial. For Helsinki, results show that two buildings, D and E, are significantly larger and greater in width and height than the others. These two large buildings are formed as producers of energy. In case of Helsinki, the OEM for the buildings D and E, are 97 % and 88 %. Taking into account that buildings A, B and C do not have any production, OEM for the building mass is 97 %. The amount of excess energy decreased with the possibility to share energy by 40 % and that corresponds to 14 % of the total energy demand of building B.

For Bucharest, results show that building E acts as a producer, building D resembles buildings from case 2 and buildings A, B and C are just optimized to consume as less as possible. Compared to producers from Helsinki on the same case, building E is rectangular shaped. This indicates that with less demanding building regulations in terms of energy efficiency and current onsite production it is not beneficial to increase energy production in respect of higher energy consumption. Use of L- and T-shapes in small buildings indicates that the solar gain from windows on should be more beneficial than use of rectangle shape and more energy efficient building shape.

4.2 Location Comparison

In this section, results are compared by location. Each case result from one location are reviewed and compared to other cases results in the same location to see how different case setups effects on the model and optimization result. Variables especially under review are window to wall ratio, specific energy consumption compared to specific import energy consumption and energy sharing between the buildings.

4.2.1 Helsinki

Helsinki represents cold climate in this study. The building regulations of Finland are adapted to cold climate and minimum requirements for energy efficiency are higher than in other location studied in this thesis. In Helsinki region, heating is assumed to be the dominant form of energy need. Solar gain from windows is assumed to be beneficial in Helsinki as it decreases the heating demand. Helsinki is relatively far from the equator and the amount of total solar radiation is smaller than in the other location. High latitude increases the share of radiation coming from lower angles which may be beneficial for vertically installed photovoltaics as the zenith angle is generally larger. Results for different cases in Helsinki are presented in Table 4.

Table 4 Case results and indicators for Helsinki

	Case 1			Case 2			Case 3			Case 4			Case 5				
		Helsinki			Helsinki			Helsinki			Helsinki				Helsinki		
Building	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	D	E
Total floor area [m2]	474,3	56,9	470,3	41,5	126,4	835,8	100,7	860,6	39,6	96,1	642,0	261,8	27,4	28,0	27,9	832,8	283,6
Nro of floors	7	1	9	1	2	10	3	10	1	1	7	3	1	1	1	10	4
Facade PV area [m2]	181	0	195	0	33	350	40/36	526/217	0/0	0	0	0	0	0	0	509	179
PV orientation	176	194	185	199	179	124	185/95	229/139	217/127	343	161	181	180	153	29	161	239
Specific energy consumption	8,84	9,15	8,99	9,44	7,60	6,20	9,74	9,43	10,14	9,86	8,58	9,26	11,29	10,18	11,34	9,47	10,22
Specific export electricity	7,6	9,2	7,6	9,4	6,7	5,0	7,5	6,7	10,1	9,9	8,6	9,3	11,3	10,2	11,3	7,5	8,1
Ratio of production to consumption	16 %	0 %	18 %	0 %	13 %	23 %	29 %	40 %	0 %	-	-	-	0 %	0 %	0 %	26 %	26 %
Export energy costs [€]	360,16	52,10	357,35	39,23	85,24	421,54	75,92	578,29	40,10	94,75	551,07	242,28	30,95	28,52	31,67	626,04	230,86
Specific energy costs [€/m2]	0,76	0,92	0,76	0,94	0,67	0,50	0,75	0,67	1,01	0,99	0,86	0,93	1,13	1,02	1,13	0,75	0,81
		Total			Total			Total			Total				Total		
Specific energy consumption		8,93			6,51			9,49			8,9				9,75		
Specific export electricity		7,68			5,43			6,93			8,9				7,9		
Ratio of production to consumption		16 %			20 %			37 %			0 %				23 %		
Total energy costs		767,65			542,65			682,22			888,10				940,44		
Total energy costs without sharing		769,61			546,01			694,31			888,10				948,05		
Specific energy costs [€/m2]		0,77			0,54			0,68			0,89				0,78		
Specific energy costs without		0,77			0,54			0,69			0,89				0,79		
	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	D	E
Onsite energy matching	99 %	-	96 %	-	99 %	94 %	96 %	90 %	-	-	-	-	-	-	-	97 %	88 %
Onsite energy fraction	14 %	-	15 %	-	11 %	19 %	23 %	29 %	-	-	-	-	-	-	-	21 %	20 %
		Total			Total			Total			Total				Total		
Onsite energy matching		98 %			96 %			91 %			-				97 %		
Onsite energy fraction		13,9 %			16,5 %			26,9 %			-				19 %		
Maximum hourly deficit		41,73			38,61			43,09			50,17				54,04		
Maximum hourly deficit without		41,73			38,61			43,09			50,17				54,04		
Maximum hourly surplus		5,11			11,15			25,33			-				8,86		
Maximum hourly surplus without		5,17			12,96			25,73			-				11,00		

Effect of window to wall ratio

In five cases, three different window to wall ratios were tested. The window to wall ratio varied from 10 to 50 %. Between case 1 and case 2 additional windows were added to the adjacent sides of the PV façade. Based on the specific energy consumption the increase of windows has decreased the energy consumption on for the total building mass from 8.93 to 6.51 kWh/m^2. Thus, the U-value of windows are higher than U-value of walls, the result indicates that the amount of solar gain dominates the increase in heat loss from conduction. This can also be interpreted when comparing the difference in specific export energy demand and specific energy demand. In case 2 the export energy demand is 1,08 kWh/m^2 lower than specific energy demand. In case 1 corresponding figure is 1,27 kWh/m^2 which means that in case 2 the increased window area dominates the optimal orientation of PV.

In case 4 the amount of window area is still increased and the PV-façade is removed and replaced with window to wall ratio of 50 %. Adjacent sides of window façade have 30 % window area like in case 2. The specific import electricity consumption is expectedly increased as the production has been taken off. The specific energy consumption, which considers only the absolute value of needed energy, is also increased compared to case 3, but is less than in case 1. This would indicate with window ratio of 50 % the amount of solar gain is not dominative.

On-site energy production

On-site energy in the model is produced with BIPV panels. Panels are installed vertically and are on one or two facades depending on the case. Cases 1 and 3 have the same specifications on other building specification expect that case 3 have two adjacent PV facades and case 1 has only one. In case 3 the total amount of PV façade area is tripled compared to case 1 and the building shapes have changed from rectangles to L-shape. L-shape has higher façade area to building volume ratio than the rectangular shape and higher total heat loss with respect to floor area. This can be interpreted from higher specific total energy consumption in case 3 than in case 1. Specific import electricity consumption was found to be lower in case 3 than in case 1, as well as the total energy costs, so the extra PV-façade generates more energy than the increased heat loss coming from the change of shape to less energy efficient one.

The performance of the solar facades in terms of produced energy to total PV area is rather stable in all cases, and the values differ from 2,81 to 3,31 kWh/m^2. The lowest value was found in case 2 and highest in case 1. In case 2 the increased amount of window area on adjacent sides to PV facades seemed to gather solar gain and based on this result the free heat gained dominated the maximum PV efficiency. In case 3 extra PV facades did not increase the efficiency in terms of production to area ratio and produced 3,11 kWh/m^2. Based on this, adding an extra PV façade on the adjacent wall does not affect significantly the performance of on-site energy production in cold climate. OEM in case 3 is 91 % which is the lowest for total building mass when compared to all cases. This indicates that increased amount of PV from the extra PV façade cannot be utilized as much in the building and the excess energy is produced when other buildings cannot utilize it.

Energy sharing

Energy sharing enable the use of excess production of electricity in other buildings. Effectiveness of energy sharing can be interpreted with comparing indicator with and without the possibility to share energy. Maximum hourly deficit indicates the maximum total electricity demand of the relative building mass. Results show that the maximum hourly deficit is same in scenarios with or without energy sharing. This indicates that the maximum consumption happens when there is no on-site production available or production of excess energy is not timed during the peak load hours.

Maximum hourly surplus indicates the maximum excess power of on-site production. Maximum hourly surplus in every scenario is smaller with energy sharing than without possibility to share energy. The difference discloses that there is excess electricity that is shared from one building to another. The greatest amount of shared energy can be found in case 5, where the number of buildings is increased from three to five. In case 5, the amount of shared energy was 38 % of total excess energy and it corresponds to 10-15% of energy demand of building A, B or C. This share is close to the OEF value of a single building in case 1 or 2.

4.2.2 Bucharest

Bucharest represents the warm climate in this study. Building regulations in Romania are not so demanding than in other location in this study. This can be seen as higher specific energy consumption in all cases. In Bucharest, demand for cooling energy is assumed to be the dominant form energy consumed and solar gains from windows is assumed to be unbeneficial. Bucharest is located closer to equator and the amount of total solar radiation is higher. The optimal slope of photovoltaic panels is closer to horizontal than in Helsinki and is unfavorable for vertically installed photovoltaic panels. Case results and indicator for Bucharest are presented in Table 5.

Table 5 Case results and indicators for Bucharest

	Case 1			Case 2			Case 3			Case 4			Case 5				
		Bucharest			Bucharest			Bucharest			Bucharest				Bucharest		
Building	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	D	E
Total floor area [m2]	312,9	45,0	642,3	44,1	506,0	449,8	35,0	928,0	37,8	32,1	452,3	515,8	40,8	45,0	37,3	173,8	903,0
Nro of floors	5	1	8	1	7	6	1	10	1	1	7	7	1	1	1	3	8
Facade PV area [m2]	93	0	201	0	204	181	0/0	526/182	0/0	0	0	0	0	0	0	39	384
PV orientation	183	192	191	190	214	182	191/101	210/120	179/89	242	183	207	176	185	16	169	220
Specific energy consumption	10,03	12,76	9,55	12,76	10,23	10,26	13,24	10,22	12,51	13,28	9,18	9,00	13,54	12,69	14,32	11,04	9,78
Specific export electricity	8,9	12,8	8,3	12,8	8,7	8,7	13,2	7,3	12,5	13,3	9,2	9,0	13,5	12,7	14,3	10,2	8,1
Ratio of production to consumption	13 %	0 %	15 %	0 %	18 %	18 %	0 %	40 %	0 %	-	-	-	0 %	0 %	0 %	8 %	21 %
Export energy costs [€]	278,40	57,38	533,47	56,27	439,85	391,42	46,39	679,16	47,32	42,57	415,00	464,43	55,22	57,11	53,40	177,46	730,60
Specific energy costs [€/m2]	0,89	1,28	0,83	1,28	0,87	0,87	1,32	0,73	1,25	1,33	0,92	0,90	1,35	1,27	1,43	1,02	0,81
		Total			Total			Total			Total				Total		
Specific energy consumption		9,85			10,36			10,41			9,2				10,34		
Specific export electricity		8,69			8,87			7,72			9,2				8,94		
Ratio of production to consumption		13 %			17 %			35 %			0 %				16 %		
Total energy costs		868,84			887,40			769,35			922,00				1071,03		
Total energy costs without sharing		869,25			887,54			772,87			922,00				1073,78		
Specific energy costs [€/m2]		0,87			0,89			0,77			0,92				0,89		
Specific energy costs without		0,87			0,89			0,77			0,92				0,89		
	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	D	E
Onsite energy matching	100 %	-	99 %	-	100 %	99,7 %	-	97,5 %	-	-	-	-	-	-	-	100 %	97 %
Onsite energy fraction	11 %	-	13 %	-	15 %	15 %	-	28 %	-	-	-	-	-	-	-	8 %	17 %
		Total			Total			Total			Total				Total		
Onsite energy matching		100 %			100 %			97,70 %			-				99 %		
Onsite energy fraction		11,7 %			14 %			25,8 %			-				13 %		
Maximum hourly deficit		55,93			58,58			60,46			57,53				70,14		
Maximum hourly deficit without		55,93			58,58			60,46			57,53				70,14		
Maximum hourly surplus		2,10			0,76			13,42			-				13,91		
Maximum hourly surplus without		2,74			1,18			13,67			-				15,48		

Effect of window to wall ratio

Different window to wall ratios were tested in three different cases. Ratios were assigned separately on different sides of the building. Based on results from cases 1 and 2, the increase in window area in case 2 has increased the energy consumption. In case 4 the PV façade is replaced with window façade with window to wall ratio of 50% and other specification are the same as in case 3. Based on the results the PV façade is more energy efficient solution than having window façade. This is according to the prior assumption that windows increase energy consumption.

On-site energy production

The amount of on-site energy production varies from one to two facades with vertically installed PV. The performance of the PV facades was in all cases close to each other and the power produced per area varied from 3,80 to 3,95 kWh/m^2. Lowest value was in case 3 which has two adjacent PV facades. Case 3 is also the case with the lowest specific import energy consumption and the highest specific energy consumption. This means that the increased production from the second PV façade dominated the energy efficiency of the buildings.

In all cases, the OEM was considerably high and the lowest was in case 3 with the value of 97,7 %. OEM of 100% means all the energy is going directly during the whole simulation. This indicates that benefit from the on-site production is not as beneficial as investing in energy efficiency by building shape within the optimization environment of Bucharest as even on the solar peak hours are not enough to match the demand.

Energy sharing

Significant energy sharing was not found in the results of Bucharest, yet on every case OEM for total building mass was higher than average OEM of separate buildings. The lowest OEM of 98 % was found in case 3 where each building had two adjacent PV facades. The results propose that the onsite production with only one PV facade is not enough in Bucharest for produce energy for sharing.

5 Discussion

In this section, the results presented in case and location comparison are being reviewed to each other and the results in general are evaluated to other studies.

Windows and energy consumption

In the model of this study, amount of window surface was controlled by changing the constraint for window to wall ratio of facades of different directions. Window to wall ratio varied from 10 to 50 % of the façade area depending on the case. Windows have greater U-value than wall structures and increase the heat loss through conduction which will increase the heating demand. Windows can also pass through solar irradiation which will decrease heating demand but sometimes increase the cooling demand.

In the result of Helsinki case 1 and 2, the increase in window surface area on opposite sides of the building from 10 % to 30 % decreased the total energy demand of the buildings. In Bucharest case 1 and 2, the effect was the opposite yet smaller. The decreased energy consumption in Helsinki with increased window area was unexpected. With correct orientation of the windows the energy performance of the building can be improved (Tagliabue et al. 2012) and in the case of Helsinki the solar gain compensating heating demand was found to dominate the increased heat losses and possible cooling demand from solar gains. Reasons for this to happen may come in cold climate where cooling demand is generally low and the high energy efficiency standards set the difference between U-values of windows and walls lower than in other locations. In study by Tuhus-Dubrow et. al (2010), similar results were achieved in building simulation for Boulder Colorado, which is also heating climate like Helsinki. In the study, optimal building shape was south facing trapezoid, where two opposite facades are pointing north and south and the facades on the sides are slightly tilted towards southeast and southwest. These slightly tilted sides increased the solar gain during midday to decrease the heating demand compared to a rectangle shaped building with a same area (Tuhus-Dubrow & Krarti 2010). Similar effect happened with the increased window area in Helsinki case 2.

In cases 2 and 4 the PV-façade of case 2 is replaced with window façade with window to wall ratio of 50 %. In both locations, this increased the total energy consumption as assumed, but in Bucharest, the maximum hourly deficit was smaller in case 4 than in case 2. Further inspection of the model revealed that the highest consumption in case 2 was on the coldest hour, i.e. hour with the lowest temperature, of the weather data. On case 4, the highest deficit was not during the hour with the lowest temperature. The hour with the lowest temperature was in the morning and the during this hour in case 4 the window façade had gathered a small amount of solar irradiation decreasing the heating demand. Also, the total amount of solar irradiation, total heating demand and total cooling demand was higher in case 4 than in case 2. Based on these results, larger window area does increase the solar gain which can be useful, but the increased heating demand in terms of increased U-value and cooling demand suggestively from solar gain have greater effect on building energy consumption. Similar results can be derived from studies (Flodberg et al. 2012) and (Torcellini et al. 2014).

On-site energy production

On-site energy production was applied in the model as installed PV area on the vertical building façade. In the results, PV facades are mainly pointing towards southwest or southeast. Based on calculations of Hamdy et al. (2013), 15 to 30 degrees from south to west is the best orientation for steep PV panel to maximize the yearly production. With this orientation, the highest daily production times during the active hours of the simulated buildings. From the result graphs, the highest amounts of excess energy can be traced during the early evening hour as the active time of the building ends and the demand of electricity for lighting and appliances stops.

The performance of the PV facades was additionally examined with the ratio of total production divided by PV area. The performance of Helsinki varied 2,81 to 3,31 kWh/m^2 and in Bucharest from 3,80 to 3,95 kWh/m^2. The performance of PV facades in different cases are presented in Table 6.

Table 6 Performance of PV facades

Performance of PV façade [kWh/m^2]	*Helsinki*	*Bucharest*	*Difference*
Case 1	3,31	3,92	16 %
Case 2	2,81	3,84	27 %
Case 3	3,11	3,80	18 %
Case 5	3,21	3,95	19 %
Average	3,11	3,88	20 %

The variation in performance of Helsinki was greater than in Bucharest meaning that in general the PV was not as dominant feature in Helsinki as in Bucharest. This is especially seen in case 2, in which the amount of window area on the adjacent sides to the PV-façade were increased and the increased solar gain from windows was used efficiently. The lowest performance was found in case 3 of both locations. Case 3 was the only case with two PV facades per building and results tell that in terms of total production, having vertical panels on two different directions with 90 degrees of separation is not efficient. When inspecting the OEF the value in case 3 is doubled in Helsinki and tripled in Bucharest compared to case 1. This indicates that case 3 would be the best for chasing nZEBs as the combination of OEF and OEM is the highest (Cao et al. 2013).

Impact of the export and import electricity cost

The model was encouraged to balance the on-site production to energy demand to replace as much import electricity as possible. This was done by setting the compensation price of surplus energy to 50 % of the cost of import electricity. The amount of surplus energy was found small in the results and the total OEM was over 90 % in all cases whether the location.

Most significant results are found in the case 5: In Helsinki, total OEM was 97 % while only one of two buildings had the OEM of 97 %. In Bucharest, the total OEM was 99 % while building which produced over 90 % of all onsite-energy had OEM of 97 %. These results show that additional benefits can be found when designing multiple buildings simultaneously. These additional benefits are e.g. load matching and energy sharing between multiple buildings or neighborhoods and these factors may come significant while the onsite production, NZEBs and even net-positive energy building emerge (Cole & Fedoruk 2014; Ala-Juusela et al. 2015; Kilkiş 2014).

Performance of the model

Based on the observation on different factors in previous parts of this section, the model performed expectedly on cases with different constraints. Most of all, features effected by the manipulated optimization constraints behaved expectedly compared to other studies considering similar actions presented in sections above.

The aim was to make the model agile yet correspondent for designers to use during the conceptual design phase. The calculation times for the optimization model on different cases varied from 15 to 30 minutes while using an average laptop. Model processes up to ten thousand populations during the simulation while the population size was two hundred.

6 Conclusions

This thesis studied the applicability of genetic algorithm in energy efficient shape optimization of multiple buildings and possibility to create a simple and fast model for designers for designing multiple buildings. Building energy optimization has been considered heavily time-consuming and complicated process even on building level and studies have been concentrating in optimizing specifically features of building one building, e.g. building shape, window size and orientation, HVAC system or yearly energy consumption.

Building energy optimization is thus rarely introduced in the design or conceptual phase in the building process. Also, concentration on building level optimization may lead to inefficiencies in terms of larger systems: When designed case by case the additional benefits from interaction between buildings, such as load matching and energy sharing, is left out and may cause problems as e.g. on-site energy production emerges.

In this thesis, optimization model of multiple buildings shape, orientation and location using GA was demonstrated and case study was conducted to review the performance of the model. Optimization model is set to choose freely the location, orientation, shape and size of a certain number of buildings. The model evaluates solutions based on the total energy costs of all buildings. In respect of swiftness and simplicity number of variables were reduced by simplifying different features. Direct comparison of energy costs is not valid thus the energy has not introduced to primary energy factor and the simulation environments are notably different depending on the location.

Building specifications and energy consumption model follow the requirements set in building regulations yet it has been developed for hourly based observation. All energy consumption is converted to electricity based on the efficiencies of different building systems. Energy production, shadowing model and solar gain follow solar irradiation from collected hourly weather data and location based solar angles. Only available on-site energy production in the model is BIPV in building façades. Fitness of the solution was evaluated based on the total energy costs of all buildings. Energy costs are calculated based on amounts and prices of import and export electricity. The price of import electricity is double the compensation price of export electricity.

Reviewing performance of the model was conducted as case study, where results from five cases with different requirements were compared to each other and contrasted to other studies. Main features under observation were the effect of window area, on-site energy production and energy sharing. Case results indicated that the model performed well and showed expected variation based on changes in specifications regarding different cases.

Increase in window to wall ratio increased the total energy demand as windows are less energy efficient than wall structure. Increased window to wall ratio changed to orientation of the buildings and balanced the amount of solar gain and on-site production differently in cold climate. The model also used other buildings as a shade to minimize solar gain and additional cooling load in warmer climate.

On-site production was set to have the highest benefit as a replacement for import energy as the export compensation was half the price of import electricity. This setting set the model to balance between optimum amount of BIPV area compared to energy efficiency.

Variation was seen in different building shapes which have higher façade to building volume ratio, e.g. L-shaped building have higher façade to building volume ratio than a rectangle. Case with two BIPV facades favored L-shape over a rectangle and the specific energy consumption was higher than in other cases, yet the overall demand for import electricity was smaller.

Energy sharing was introduced in the model as possibility for buildings to use excess energy from other buildings on current hour. Model did not include any energy storage and surplus energy was sold during the same hour it was produced. Compensation of export electricity was half the price of import electricity. Optimization did not show significant amounts of energy sharing in cases where three buildings were simulated, yet the costs were lower with energy sharing than without it in the resulting scenarios. In case with five buildings, some of the simulated buildings could be specified as producers and other buildings as minimizers. Producers had large BIPV and amount of excess electricity was higher than in other buildings in any case. Significant was that OEM of all buildings was higher than the OEM of separate buildings, especially regarding the producers.

Optimization model developed in this thesis performed well in the tested cases and responded to different specifications according to expectations and results of relevant studies. For the model to become a practical tool for designers in conceptual phase looking for efficient entities, further research and specification are needed. Current model accounts only for buildings consuming electricity and on-site production is limited to the vertical BIPV. With limitations of this thesis some parts of the models were simplified, e.g. shadowing model and some parts of the energy model, and to evaluated the full potential of the current model, these parts should be specified.

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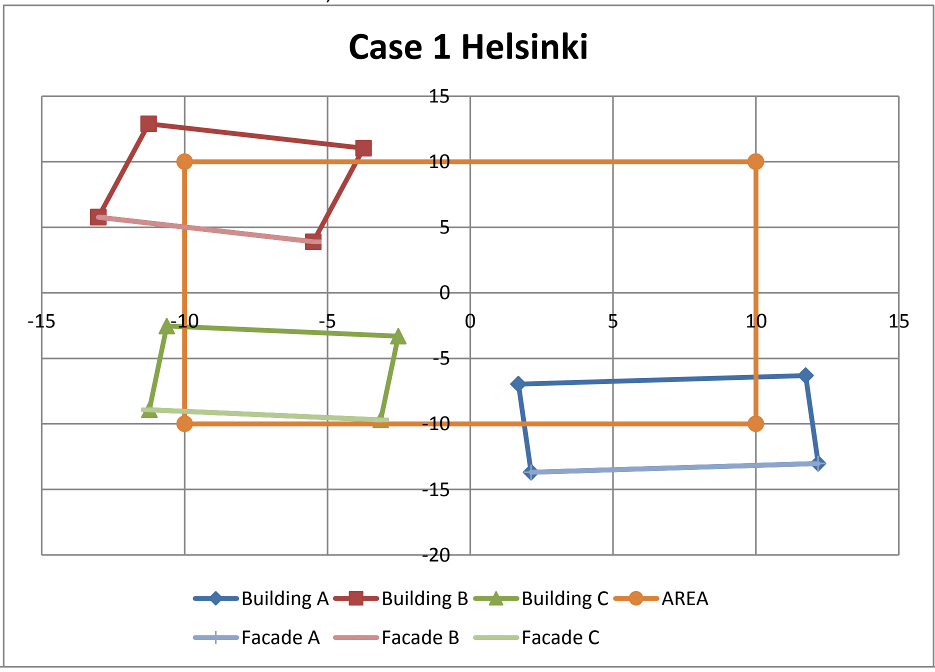
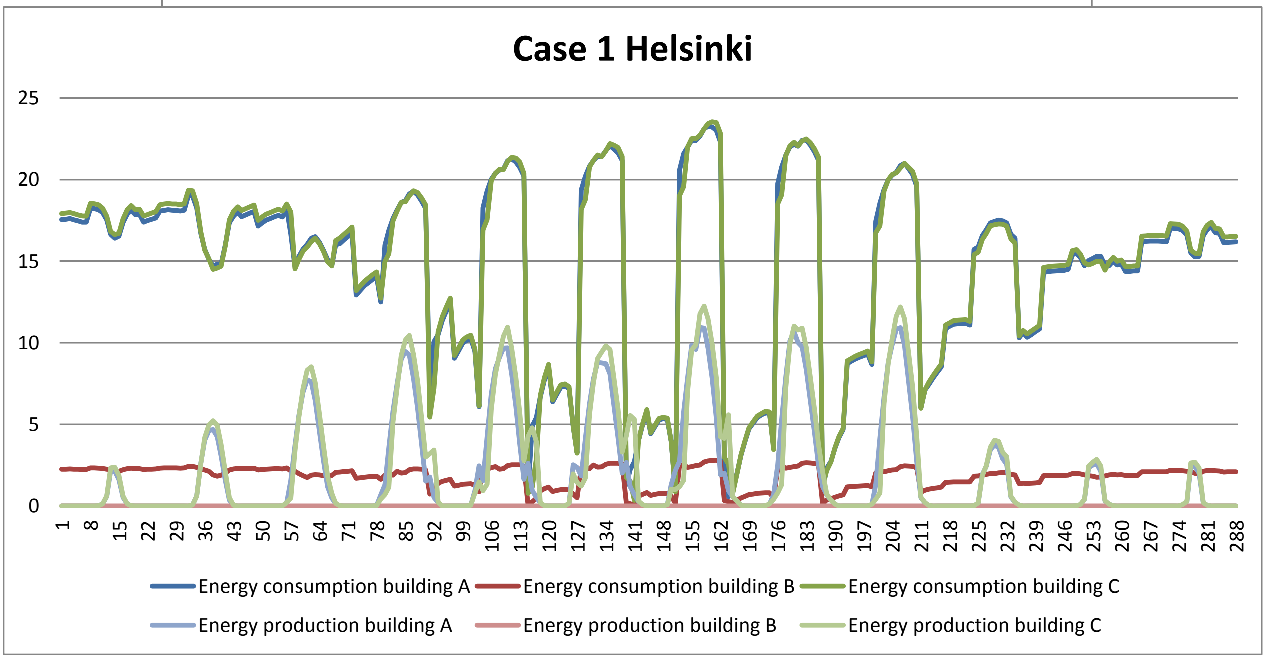
Appendixes

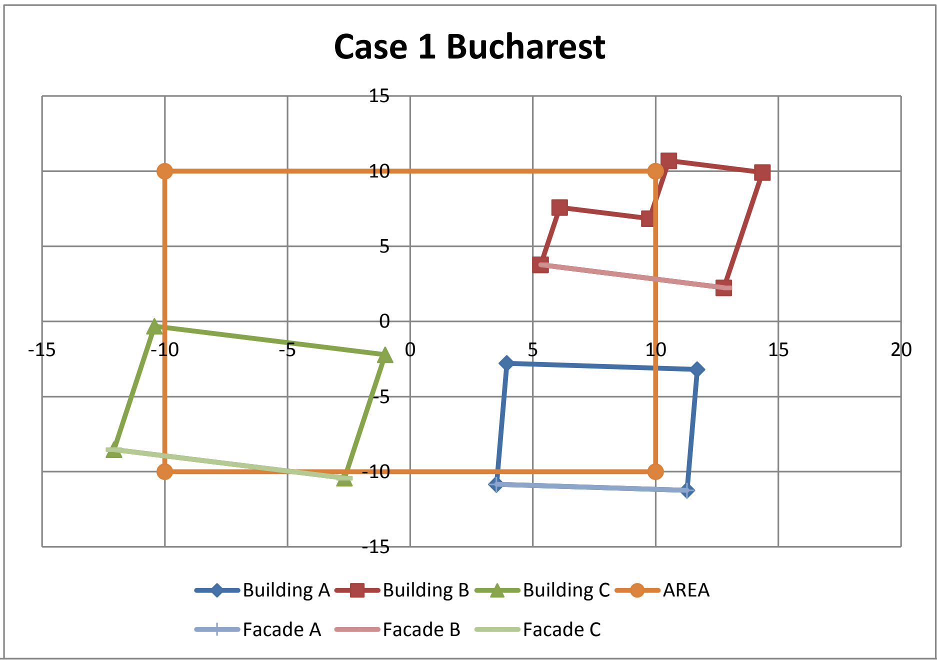
Results	Building A	Building B	Building C
Floor/roof area	67,75	56,91	52,25
Total area	474,28	56,91	470,27
Wall area	705,53	90,56	786,18
Facade area	211,48	23,25	219,73
Nro of floors	7	1	9
PV-facade area	181,27	0,00	195,31
Compass orientation	176,23	193,90	185,45
	Building A	Building B	Building C
Export elec. need	3601,61	520,97	3573,49
Energy production	593,07	0,00	654,43
Surplus energy	4,81	0,00	24,93
Total demand	7686,61		
Total surplus	20,28		
Energy price	0,10	€/kWh	3,31
Surplus energy compensati	0,05	€/kWh	
Total	769,37 €		
Total total	767,65 €		

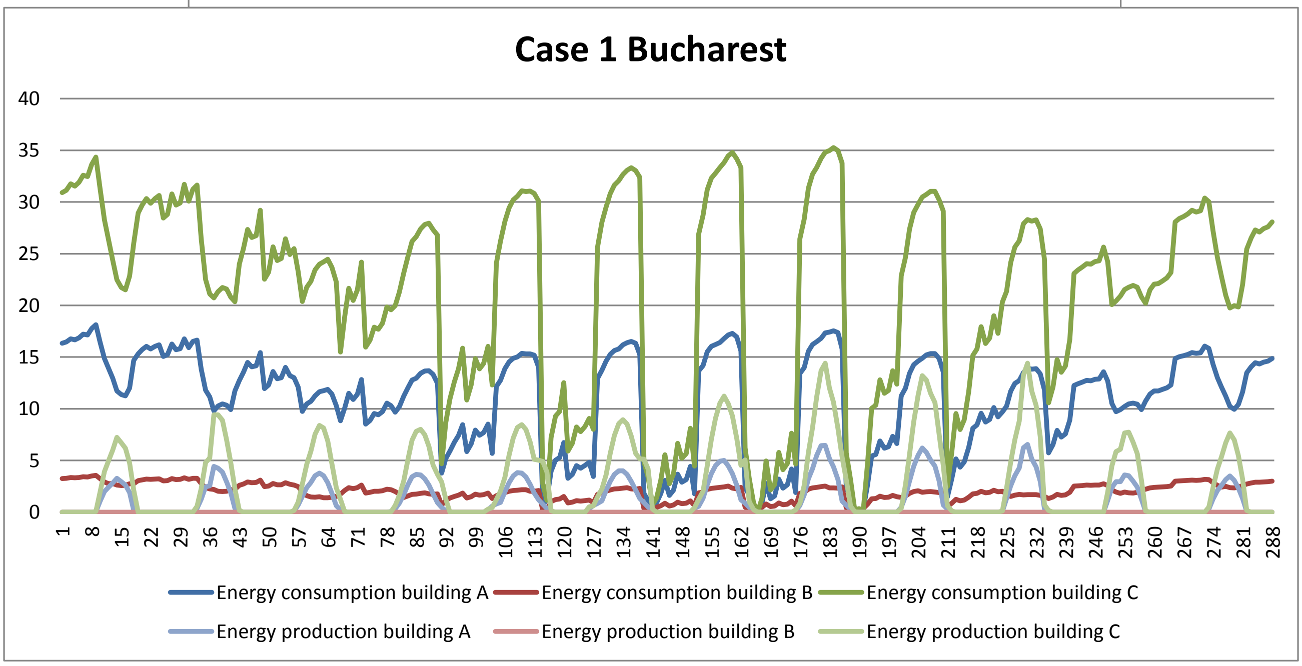




Bucharest Appendix 1 (2/10)

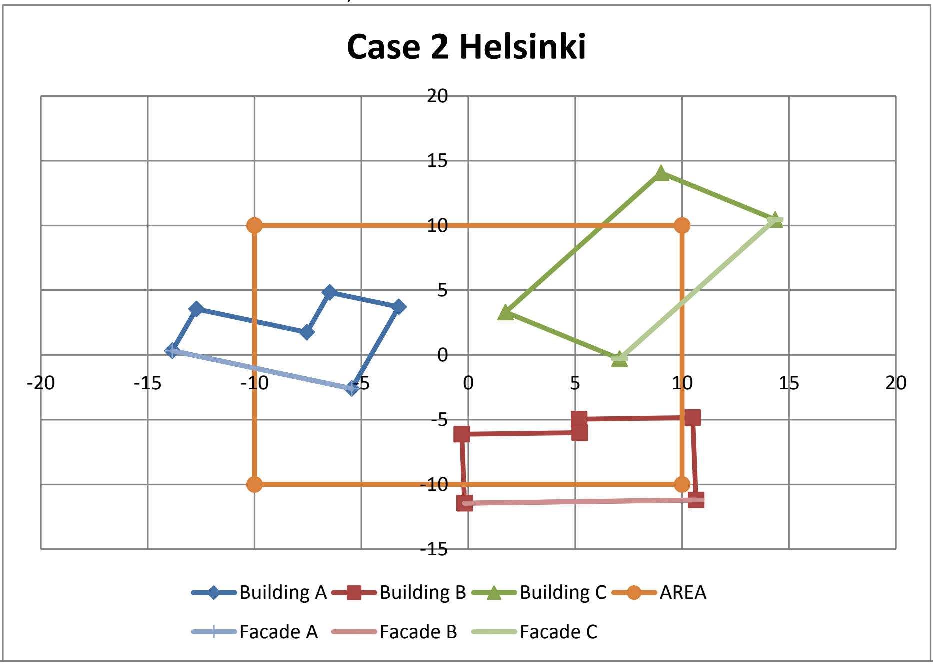
Results	Building A		Building B	Building C
Floor/roof area	62,59		44,98	80,29
Total area	312,94		44,98	642,30
Wall area	474,75		92,72	862,12
Facade area	116,51		22,87	229,95
Nro of floors	5		1	8
PV facade area	93,21		0,00	201,21
Compass orientation	182,99		191,55	191,38
	Building A		Building B	Building C
Export elec. need	2783,99		573,82	5334,73
Energy production	353,93		0,00	800,94
Surplus energy	0,09		0,00	5,92
Total demand	8690,24			
Total surplus	3,71			
Energy price	0,10	€/kWh		3,92
Surplus energy compensat	0,05	€/kWh		
Total	869,25	€		
Total total	868,84	€		

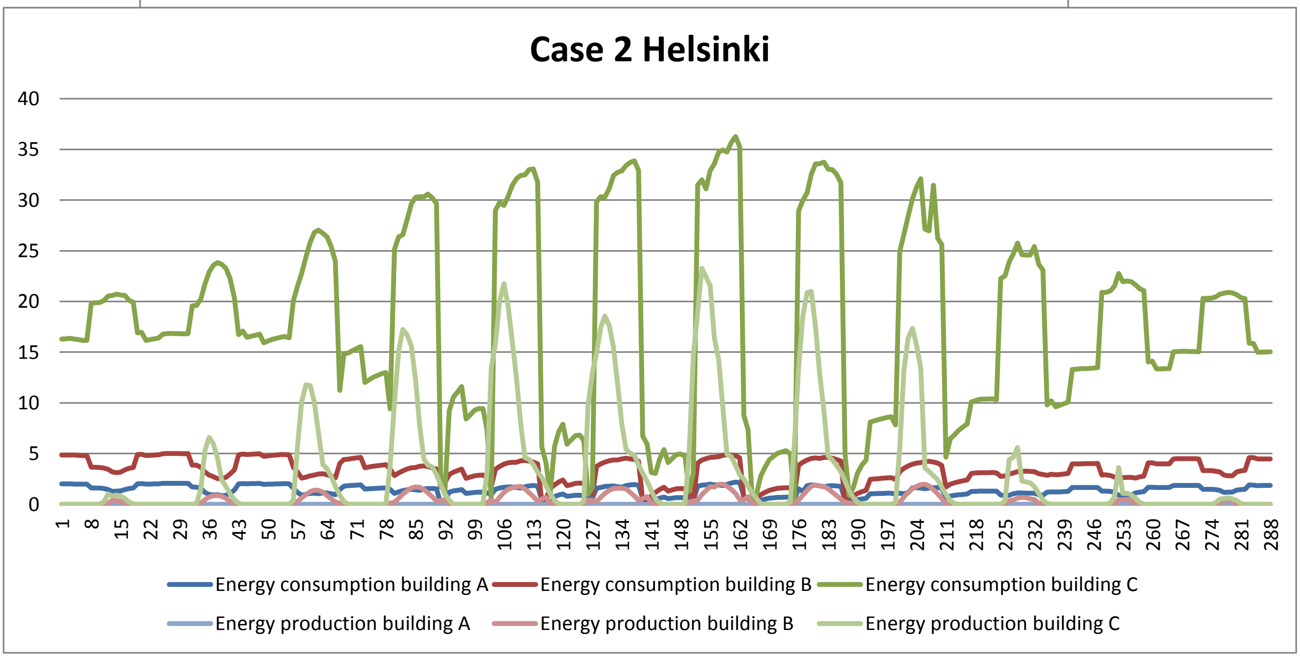




Helsinki

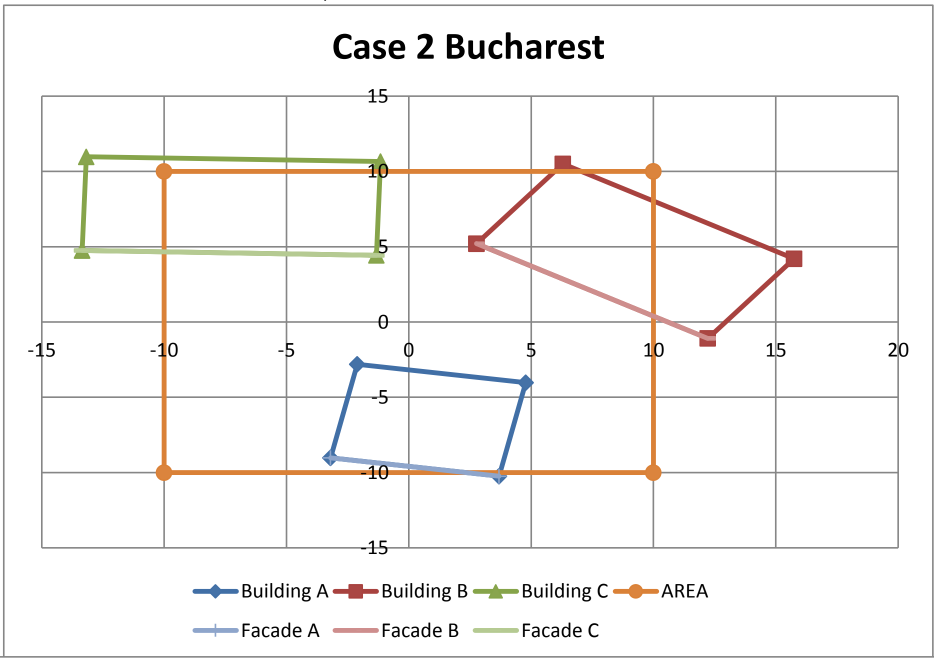
Results	Building A	Building B	Building C
Floor/roof area	41,54	63,20	83,58
Total area	41,54	126,41	835,81
Wall area	93,43	206,40	1165,19
Facade area	26,68	65,01	389,43
Nro of floors	1	2	10
PV facade area	0,00	32,50	350,49
Compass orientation	199,22	178,67	124,07
	Building A	Building B	Building C
Export elec. need	392,31	852,44	4215,36
Energy production	0,00	108,63	968,84
Surplus energy	0,00	1,29	55,36
Total demand	5449,56		
Total surplus	46,09		
Energy price	0,10 €/kWh		2,81
Surplus energy compensati	0,05 €/kWh		
Total	546,01 €		
Total total	542,65 €		

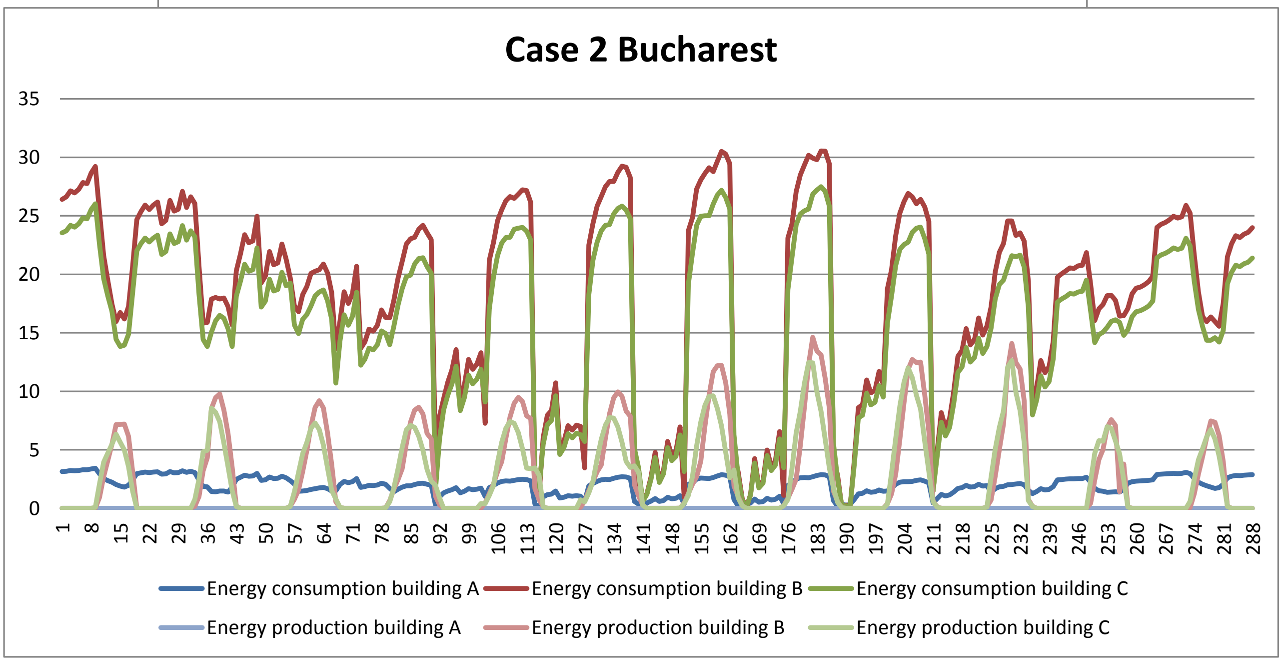




Bucharest Appendix 1 (4/10)

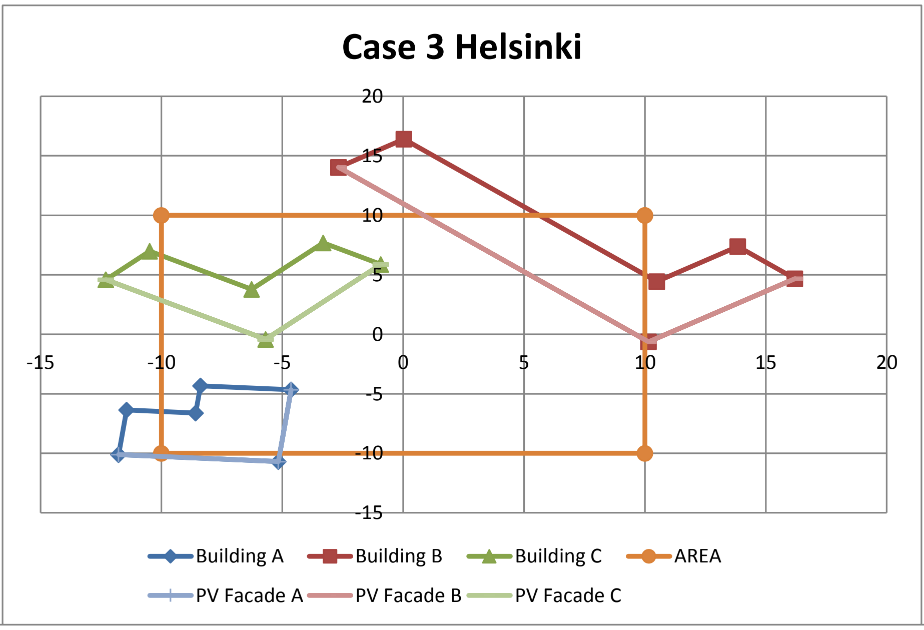
Results	Building A	Building B	Building C
Floor/roof area	44,11	72,29	74,97
Total area	44,11	506,02	449,80
Wall area	79,80	744,35	657,48
Facade area	20,96	238,52	216,60
Nro of floors	1	7	6
PV facade area	0,00	204,44	180,50
Compass orientation	189,98	213,69	181,53
	Building A	Building B	Building C
Export elec. need	562,68	4398,46	3914,24
Energy production	0,00	778,45	701,20
Surplus energy	0,00	0,00	1,78
Total demand	8874,35		
Total surplus	0,76		
Energy price	0,10 €/kWh		3,84
Surplus energy compensati	0,05 €/kWh		
Total	887,54 €		
Total total	887,40 €		

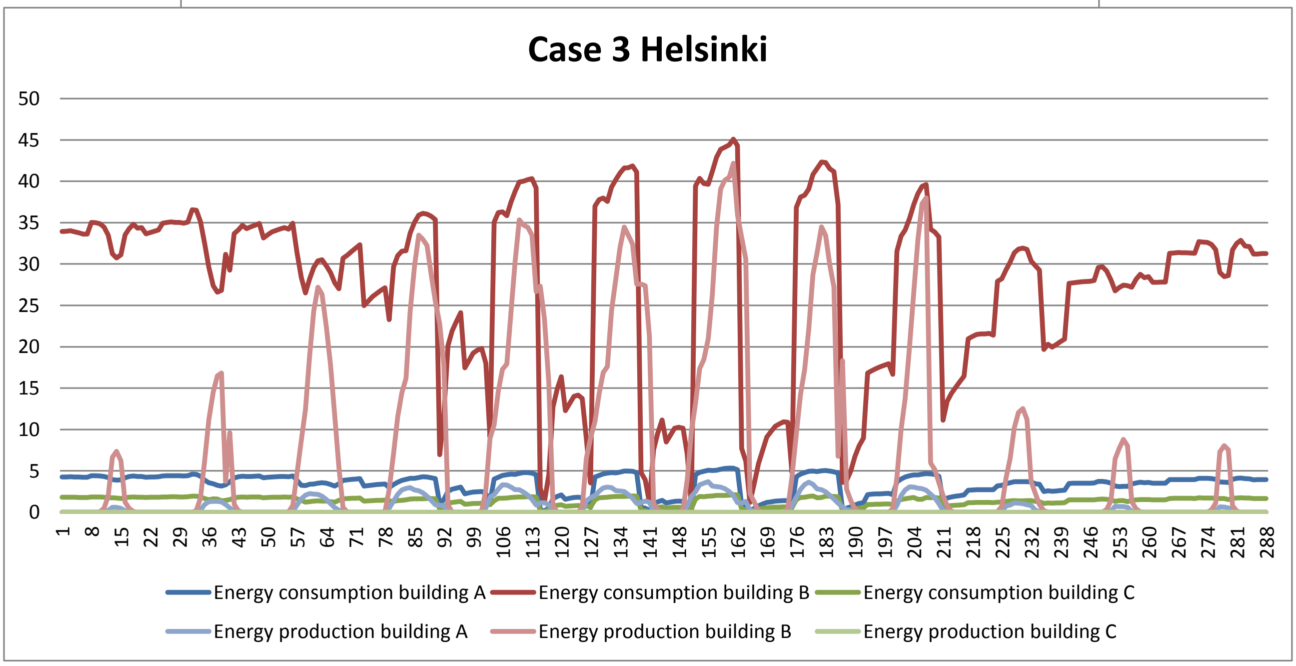




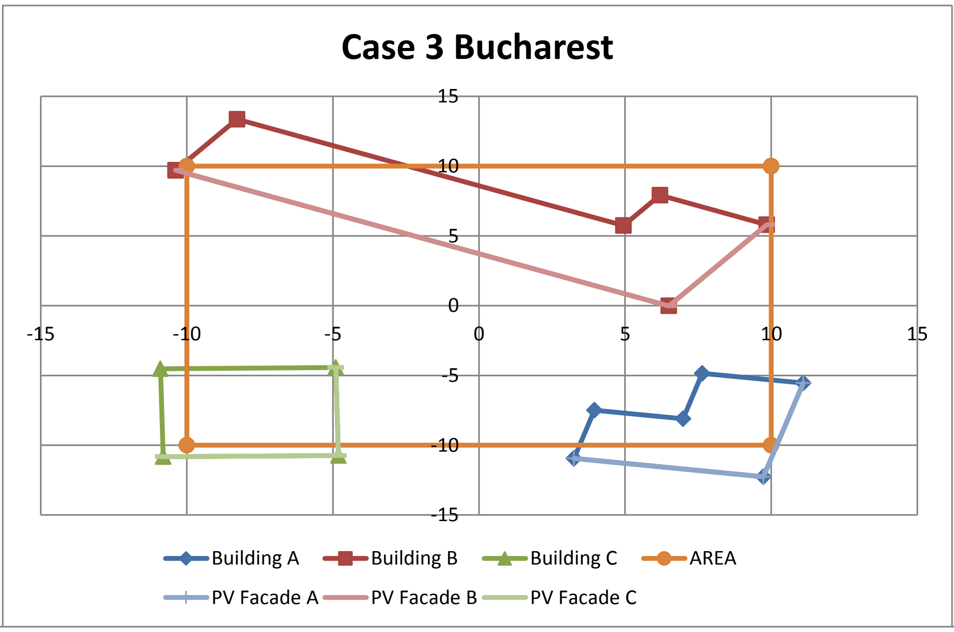
Helsinki | Appendix 1 (5/10)

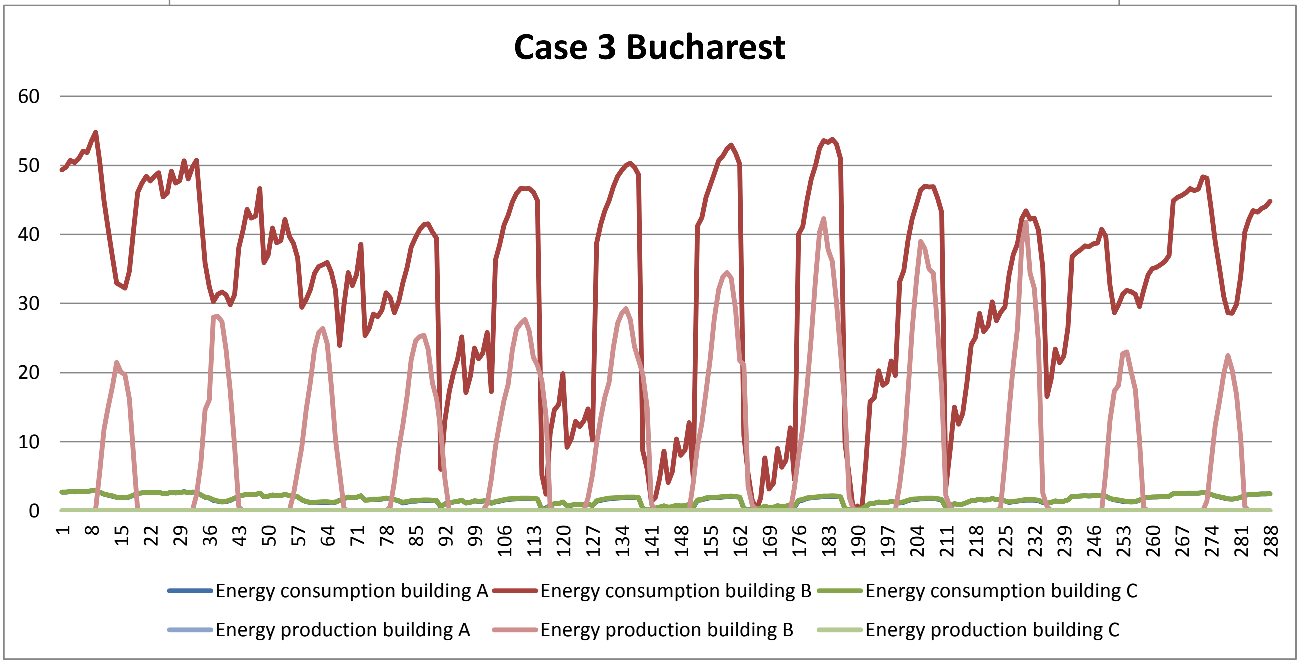
Results	Building A	Building B	Building C
Floor/roof area	33,57	86,06	39,55
Total area	100,72	860,57	39,55
Wall area	228,24	1651,66	97,11
Nro of floors	3	10	1
PV facade 1 area	39,77	526,05	0,00
PV facade 1 orientation	185,05	228,82	217,18
PV facade 2 area	36,31	217,20	0,00
PV facade 2 orientation	95,05	138,82	127,18
	Building A	Building B	Building C
Export elec. need	759,23	5782,87	400,99
Energy production	221,37	2329,63	0,00
Surplus energy	9,90	225,97	0,00
Total demand	6937,24		
Total surplus	230,02		
Energy price	0,10 €/kWh		3,11
Surplus energy compensati	0,05 €/kWh		
Total	693,81 €		
Total total	682,22 €		





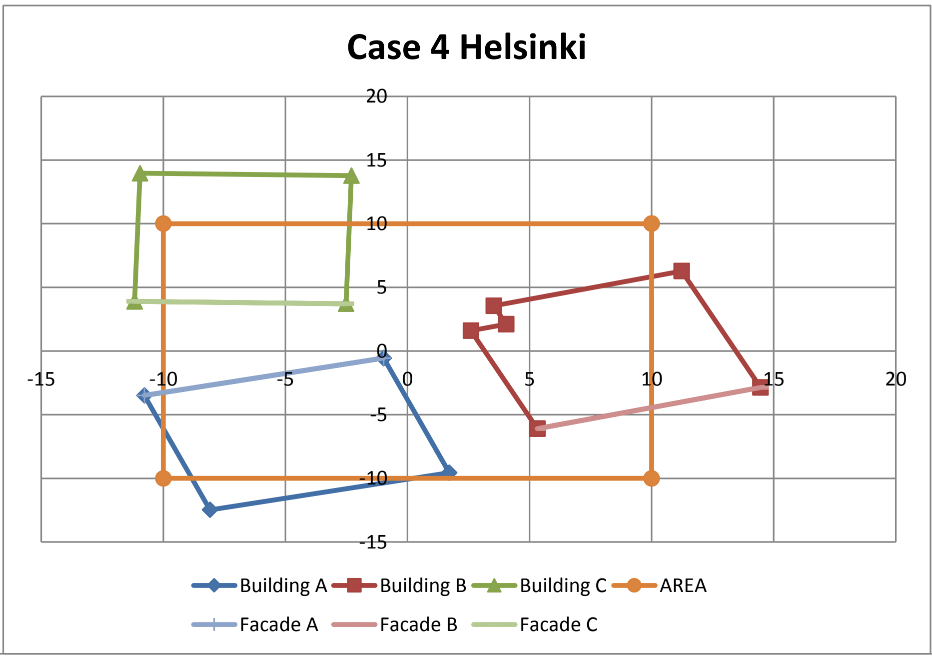
Results	Building A	Building B	Building C
Floor/roof area	35,04	92,80	37,84
Total area	35,04	928,01	37,84
Wall area	80,76	1572,17	73,84
Nro of floors	1	10	1
PV facade 1 area	0,00	525,91	0,00
PV facade 1 orientation	191,47	209,95	179,19
PV facade 2 area	0,00	181,57	0,00
PV Facade 2 orientation	101,47	119,95	89,19
	Building A	Building B	Building C
Export elec. need	463,88	6791,57	473,23
Energy production	0,00	2691,91	0,00
Surplus energy	0,00	66,13	0,00
Total demand	7724,51		
Total surplus	61,95		
Energy price	0,10 €/kWh		3,80
Surplus energy compensati	0,05 €/kWh		
Total	772,87 €		
Total total	769,35 €		

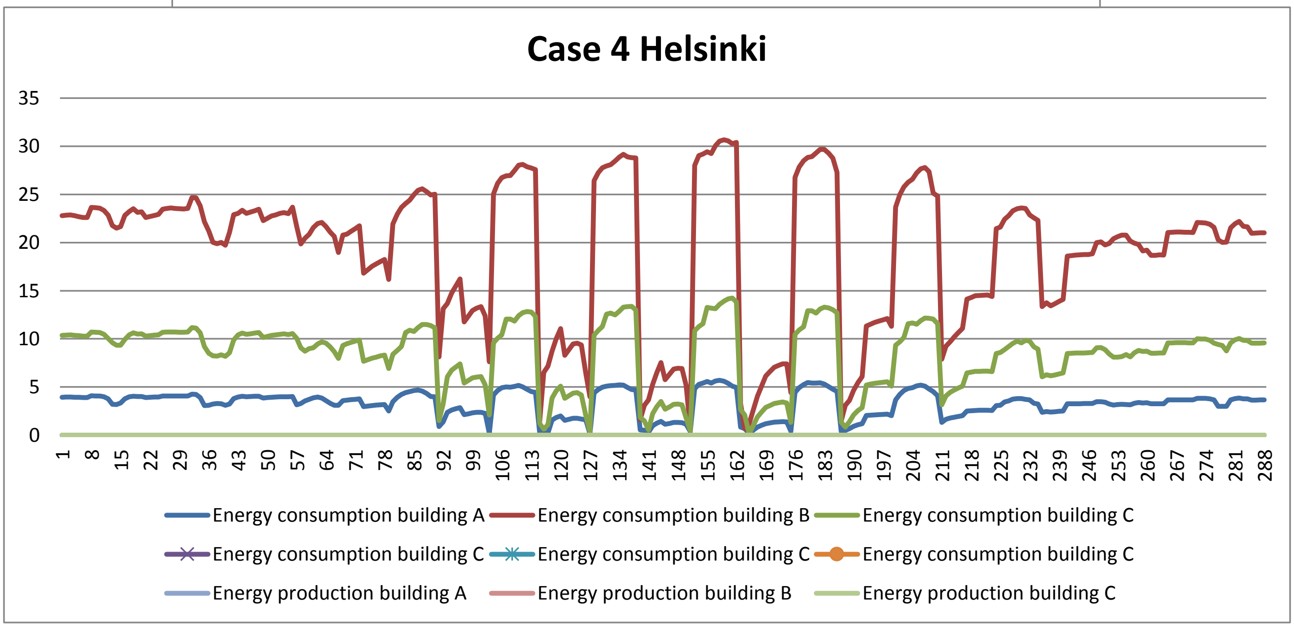




Results	Building A	Building B	Building C
Floor/roof area	96,05	91,71	87,26
Total area	96,05	641,98	261,78
Wall area	117,71	814,73	337,25
Facade area	30,67	203,69	77,96
Nro of floors	1,0	7,0	3,0
PV facade area	0,00	0,00	0,00
Compass orientation	343,35	160,53	181,25
	Building A	Building B	Building C
Energy consumption	947,51	5510,69	2422,83
Energy production	0,00	0,00	0,00
Surplus energy	0,00	0,00	0,00
Total demand	8881,04		
Total surplus	0,00		
Energy price	0,10 €/kWh		
Surplus energy compensati	0,05 €/kWh		

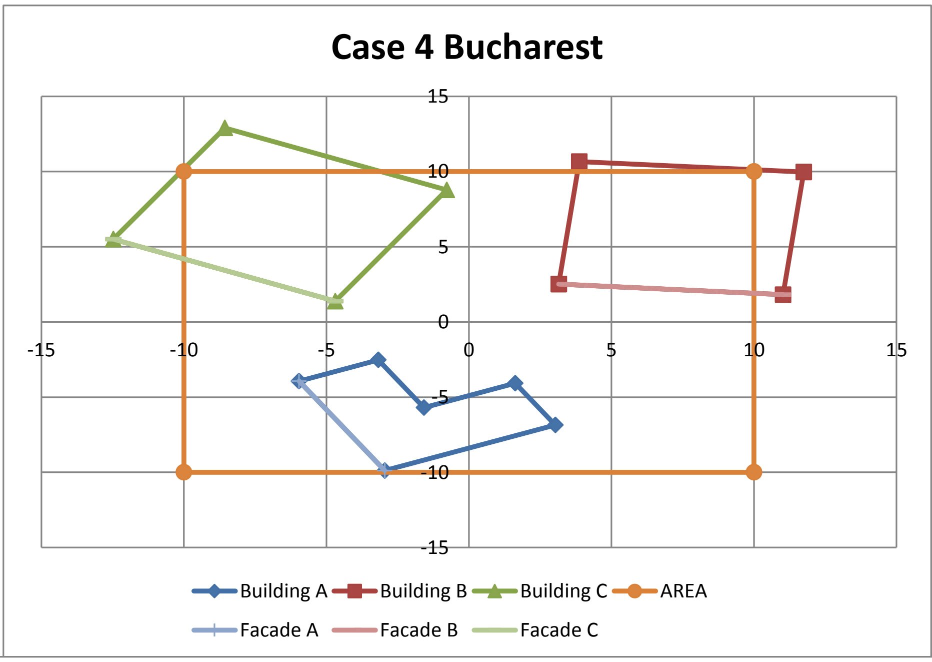
Total	888,10 €	No shared excess power
Total total	888,10 €	Shared excess power = 1 total consumption and produ

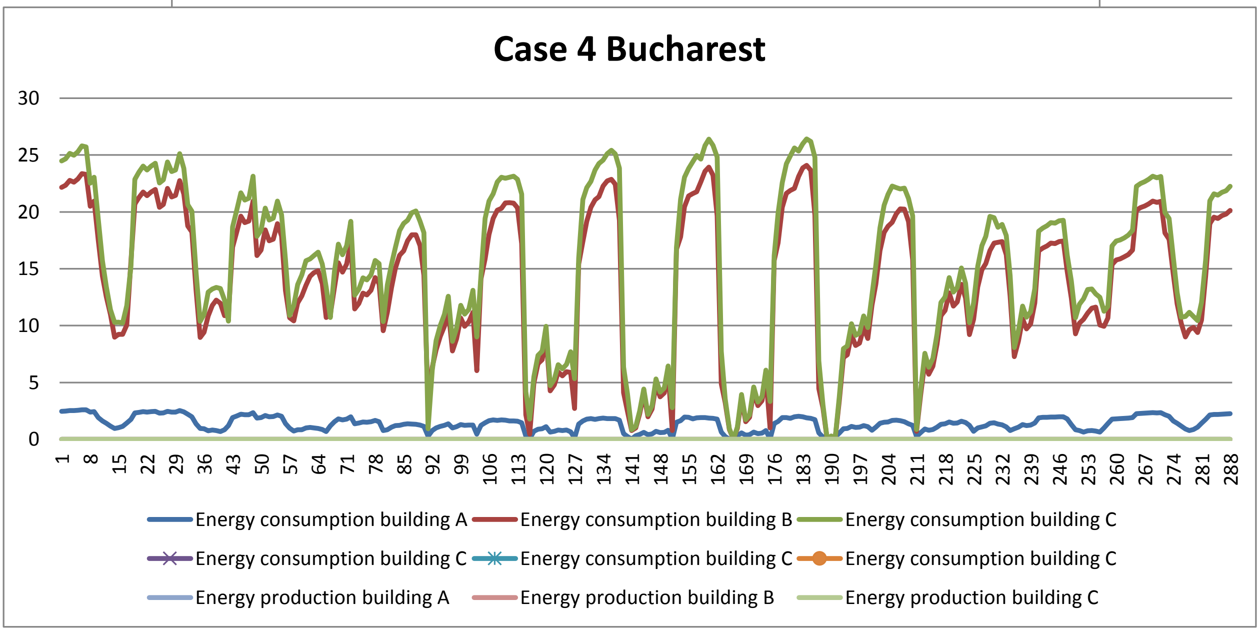




Bucharest

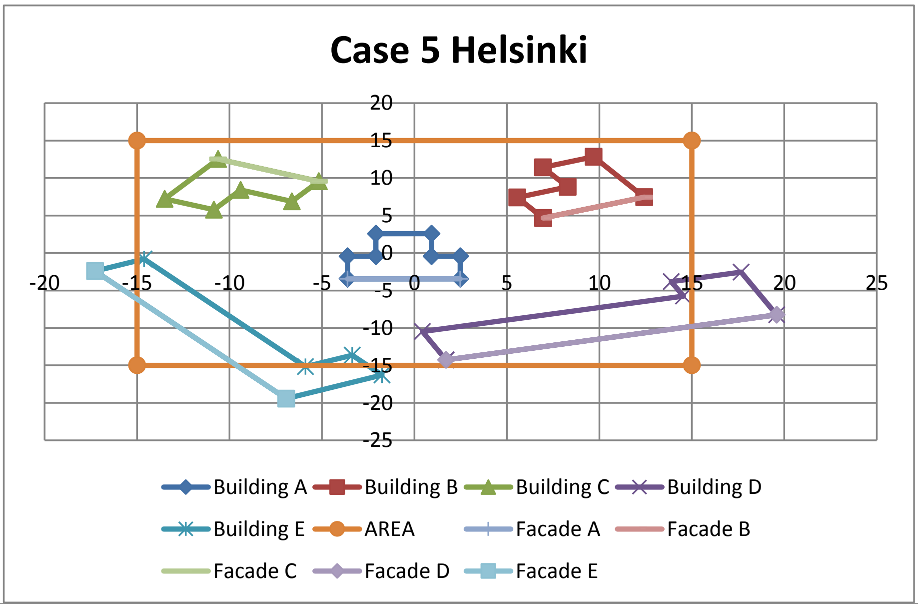
<u>Results</u>	Building A	Building B	Building C
Floor/roof area	32,06	64,62	73,69
Total area	32,06	452,31	515,81
Wall area	80,39	675,31	721,31
Facade area	20,04	166,15	185,01
Nro of floors	1,0	7,0	7,0
PV facade area	0,00	0,00	0,00
Compass orientation	242,18	183,00	207,46
	Building A	Building B	Building C
Energy consumption	425,66	4149,99	4644,35
Energy production	0,00	0,00	0,00
Surplus energy	0,00	0,00	0,00
Total demand	9220,00		
Total surplus	0,00		
Energy price	0,10	€/kWh	
Surplus energy compensati	0,05	€/kWh	
Total	922,00 €		
Total total	922,00 €		

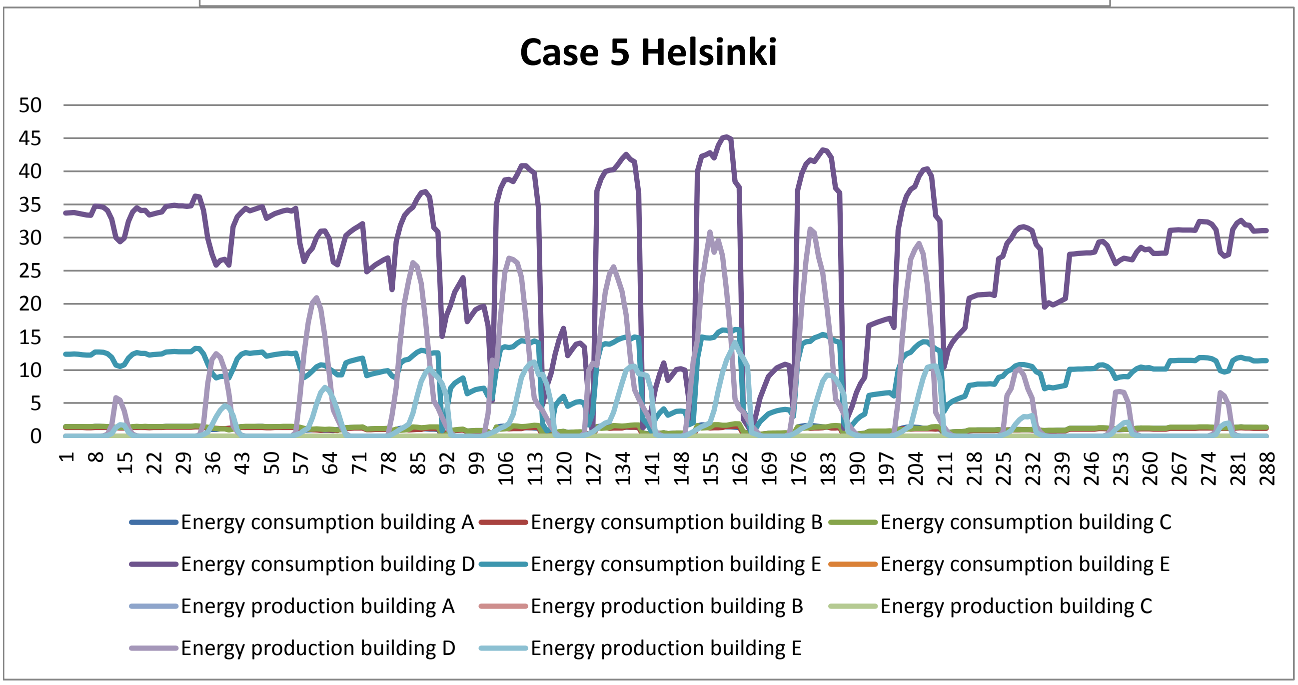




Helsinki Appendix 1 (9/10)

Results	Building A	Building B	Building C	Building D	Building E
Floor/roof area	27,41	28,00	27,94	83,28	70,91
Total area	27,41	28,00	27,94	832,83	283,62
Wall area	72,71	73,05	73,45	1493,29	623,28
Facade area	18,26	18,41	18,61	565,98	238,96
Nro of floors	1	1	1	10	4
Facade PV area	0,00	0,00	0,00	509,38	179,22
Compass orientatior	179,92	153,00	28,68	161,42	238,71
	Building A	Building B	Building C	Building D	Building E
Export elec. need	309,52	285,19	316,75	6260,37	2308,64
Energy production	0,00	0,00	0,00	1622,62	589,00
Surplus energy	0,00	0,00	0,00	41,12	68,98
Total demand	9438,48				
Total surplus	68,10				
Energy price	0,10 €/kWh		3,21		
Surplus energy comp	0,05 €/kWh				
Total	948,05 €				
Total total	940,44 €				

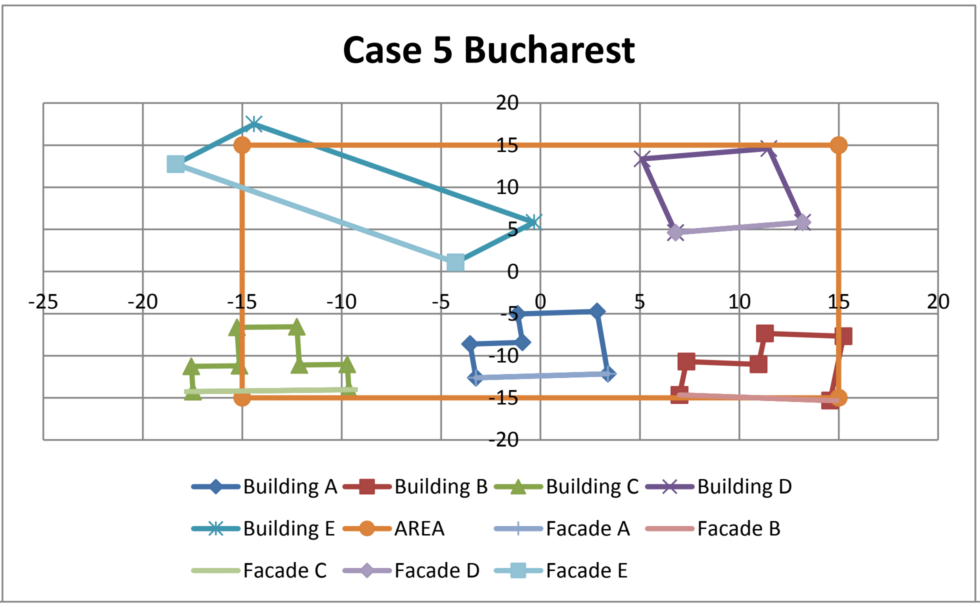


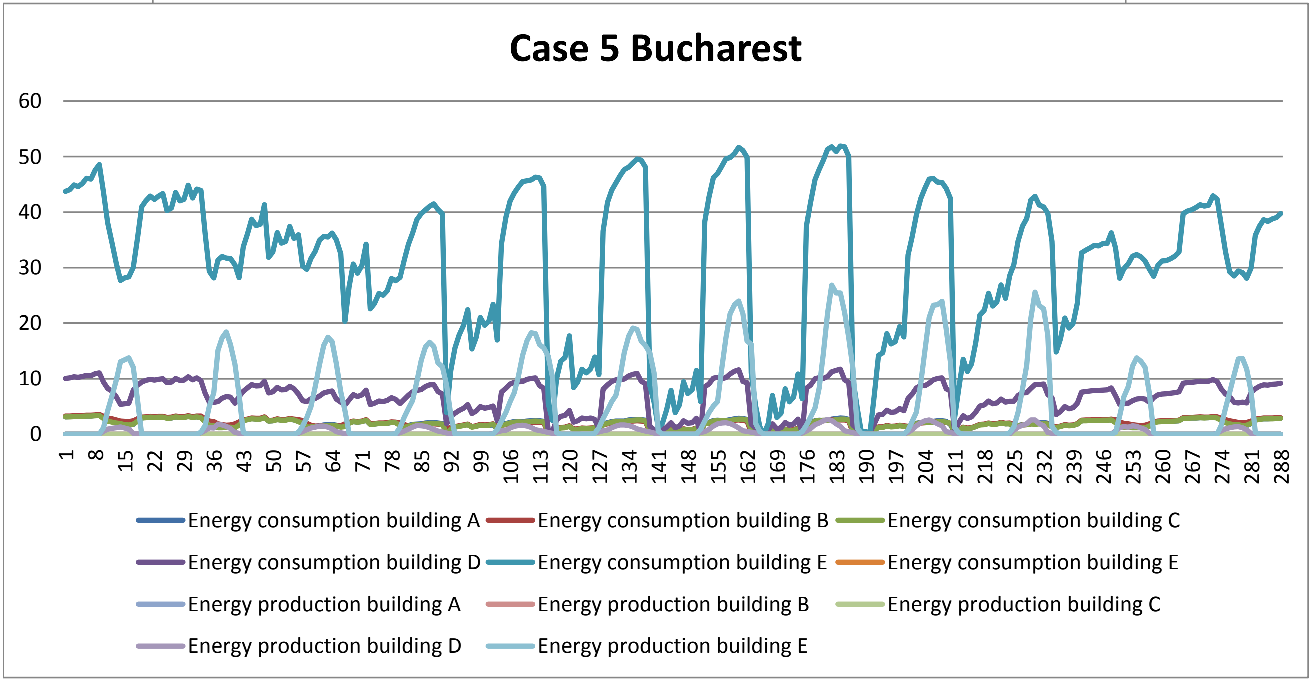


Bucharest

Appendix 1 (10/10)

Results	Building A	Building B	Building C	Building D	Building E
Floor/roof area	40,78	45,01	37,30	57,92	112,88
Total area	40,78	45,01	37,30	173,77	903,02
Wall area	85,13	91,84	92,37	277,41	1173,97
Facade area	20,29	22,96	23,53	58,48	438,82
Nro of floors	1	1	1	3	8
PV facade area	0,00	0,00	0,00	38,99	383,97
Compass orientatior	176,02	184,92	15,67	169,24	220,07
	Building A	Building B	Building C	Building D	Building E
Export elec. need	552,16	571,08	534,01	1774,56	7305,95
Energy production	0,00	0,00	0,00	144,11	1527,32
Surplus energy	0,00	0,00	0,00	0,17	39,51
Total demand	10722,56				
Total surplus	24,47				
Energy price	0,10	€/kWh	3,95		
Surplus energy comp	0,05	€/kWh			
Total	1073,78 €				
Total total	1071,03 €				





	Case 1			Case 1			Case 2			Case 2		
	Helsinki			Bucharest			Helsinki			Bucharest		
Building	A	B	C	A	B	C	A	B	C	A	B	C
Total floor area [m2]	474,3	56,9	470,3	312,9	45,0	642,3	41,5	126,4	835,8	44,1	506,0	449,8
Nro of floors	7	1	9	5	1	8	1	2	10	1	7	6
Facade PV area [m2]	181	0	195	93	0	201	0	33	350	0	204	181
PV orientation	176	194	185	183	192	191	199	179	124	190	214	182
Specific energy consumption [kWh/m2]	8,84	9,15	8,99	10,03	12,76	9,55	9,44	7,60	6,20	12,76	10,23	10,26
Specific export electricity consumption	7,6	9,2	7,6	8,9	12,8	8,3	9,4	6,7	5,0	12,8	8,7	8,7
Ratio of production to consumption	16 %	0 %	18 %	13 %	0 %	15 %	0 %	13 %	23 %	0 %	18 %	18 %
Export energy costs [€]	360,16	52,10	357,35	278,40	57,38	533,47	39,23	85,24	421,54	56,27	439,85	391,42
Specific energy costs [€/m2]	0,76	0,92	0,76	0,89	1,28	0,83	0,94	0,67	0,50	1,28	0,87	0,87
		Total			Total			Total			Total	
Specific energy consumption [kWh/m2]		8,93			9,85			6,51			10,36	
Specific export electricity consumption		7,68			8,69			5,43			8,87	
Ratio of production to consumption		16 %			13 %			20 %			17 %	
Total energy costs		767,65			868,84			542,65			887,40	
Total energy costs without sharing		769,61			869,25			546,01			887,54	
Specific energy costs [€/m2]		0,77			0,87			0,54			0,89	
Specific energy costs without sharing[€/m2]		0,77			0,87			0,54			0,89	
	A	B	C	A	B	C	A	B	C	A	B	C
Onsite energy matching	99 %	-	96 %	100 %	-	99 %	-	99 %	94 %	-	100 %	99,7 %
Onsite energy fraction	14 %	-	15 %	11 %	-	13 %	-	11 %	19 %	-	15 %	15 %
		Total			Total			Total			Total	
Onsite energy matching		98 %			100 %			96 %			100 %	
Onsite energy fraction		13,9 %			11,7 %			16,5 %			14 %	
Maximum hourly deficit		41,73			55,93			38,61			58,58	
Maximum hourly deficit without sharing		41,73			55,93			38,61			58,58	
Maximum hourly surplus		5,11			2,10			11,15			0,76	
Maximum hourly surplus without sharing		5,17			2,74			12,96			1,18	

	Case 3			Case 3			Case 4			Case 4		
	Helsinki			Bucharest			Helsinki			Bucharest		
Building	A	B	C	A	B	C	A	B	C	A	B	C
Total floor area [m2]	100,7	860,6	39,6	35,0	928,0	37,8	96,1	642,0	261,8	32,1	452,3	515,8
Nro of floors	3	10	1	1	10	1	1	7	3	1	7	7
Facade PV area [m2]	40/36	526/217	0/0	0/0	526/182	0/0	0	0	0	0	0	0
PV orientation	185/95	229/139	217/127	191/101	210/120	179/89	343	161	181	242	183	207
Specific energy consumption [kWh/m2]	9,74	9,43	10,14	13,24	10,22	12,51	9,86	8,58	9,26	13,28	9,18	9,00
Specific export electricity consumption	7,5	6,7	10,1	13,2	7,3	12,5	9,9	8,6	9,3	13,3	9,2	9,0
Ratio of production to consumption	29 %	40 %	0 %	0 %	40 %	0 %	-	-	-	-	-	-
Export energy costs [€]	75,92	578,29	40,10	46,39	679,16	47,32	94,75	551,07	242,28	42,57	415,00	464,43
Specific energy costs [€/m2]	0,75	0,67	1,01	1,32	0,73	1,25	0,99	0,86	0,93	1,33	0,92	0,90
		Total			Total			Total			Total	
Specific energy consumption [kWh/m2]		9,49			10,41			8,9			9,2	
Specific export electricity consumption		6,93			7,72			8,9			9,2	
Ratio of production to consumption		37 %			35 %			0 %			0 %	
Total energy costs		682,22			769,35			888,10			922,00	
Total energy costs without sharing		694,31			772,87			888,10			922,00	
Specific energy costs [€/m2]		0,68			0,77			0,89			0,92	
Specific energy costs without sharing[€/m2]		0,69			0,77			0,89			0,92	
	A	B	C	A	B	C	A	B	C	A	B	C
Onsite energy matching	96 %	90 %	-	-	97,5 %	-	-	-	-	-	-	-
Onsite energy fraction	23 %	29 %	-	-	28 %	-	-	-	-	-	-	-
		Total			Total			Total			Total	
Onsite energy matching		91 %			97,70 %			-			-	
Onsite energy fraction		26,9 %			25,8 %			-			-	
Maximum hourly deficit		43,09			60,46			50,17			57,53	
Maximum hourly deficit without sharing		43,09			60,46			50,17			57,53	
Maximum hourly surplus		25,33			13,42			-			-	
Maximum hourly surplus without sharing		25,73			13,67			-			-	

	Case 5					Case 5				
	Helsinki					Bucharest				
Building	A	B	C	D	E	A	B	C	D	E
Total floor area [m2]	27,4	28,0	27,9	832,8	283,6	40,8	45,0	37,3	173,8	903,0
Nro of floors	1	1	1	10	4	1	1	1	3	8
Facade PV area [m2]	0	0	0	509	179	0	0	0	39	384
PV orientation	180	153	29	161	239	176	185	16	169	220
Specific energy consumption [kWh/m2]	11,29	10,18	11,34	9,47	10,22	13,54	12,69	14,32	11,04	9,78
Specific export electricity consumption	11,3	10,2	11,3	7,5	8,1	13,5	12,7	14,3	10,2	8,1
Ratio of production to consumption	0 %	0 %	0 %	26 %	26 %	0 %	0 %	0 %	8 %	21 %
Export energy costs [€]	30,95	28,52	31,67	626,04	230,86	55,22	57,11	53,40	177,46	730,60
Specific energy costs [€/m2]	1,13	1,02	1,13	0,75	0,81	1,35	1,27	1,43	1,02	0,81
			Total					Total		
Specific energy consumption [kWh/m2]			9,75					10,34		
Specific export electricity consumption			7,9					8,94		
Ratio of production to consumption			23 %					16 %		
Total energy costs			940,44					1071,03		
Total energy costs without sharing			948,05					1073,78		
Specific energy costs [€/m2]			0,78					0,89		
Specific energy costs without sharing[€/m2]			0,79					0,89		
	A	B	C	D	E	A	B	C	D	E
Onsite energy matching	-	-	-	97 %	88 %	-	-	-	100 %	97 %
Onsite energy fraction	-	-	-	21 %	20 %	-	-	-	8 %	17 %
			Total					Total		
Onsite energy matching			97 %					99 %		
Onsite energy fraction			19 %					13 %		
Maximum hourly deficit			54,04					70,14		
Maximum hourly deficit without sharing			54,04					70,14		
Maximum hourly surplus			8,86					13,91		
Maximum hourly surplus without sharing			11,00					15,48		